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TRAIN RESISTANCE.

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(Continued from the January issue.)

(*e*) It is well known that, for a given journal, the coefficient of friction depends upon the "velocity of rubbing," *i. e.* upon the velocity with which the surface of the journal moves, as it turns, in the bearing.

The influence of velocity upon journal friction and upon train resistance has been made the subject of careful experimental study, by several observers, the earliest and most important investigations in this country being those of Mr. A. M. Wellington, and of Prof. R. H. Thurston. Mr. Wellington's experiments, made in 1878, are reported in his interesting paper, read before the American Society of Civil Engineers, in 1884. (An abstract of this paper is given in Mr. Wellington's work on "Railway Location," in Appendix B). Professor Thurston's investigations, which were begun at about the same date, extended over a period of several years. The principal results of Professor Thurston's experiments are to be found in his treatise on "Friction and Lost Work." The curves shown in Figs. 7 and 8 have been plotted from some of the tables of results contained in this work. Fig. 7 contains two sets of curves which correspond, respectively, to bearing pressures of 100 and 200 lbs. per square inch. Each set contains seven

curves, corresponding, respectively, to different temperatures, ranging between 90° F and 150° F. As these curves clearly indicate, the coefficient of friction, in any given case, is highest when the velocity is lowest, or, in fact, when the motion is so slight as to be barely perceptible, such as when starting very slowly. The friction found at this very low velocity has been variously called the "friction of rest," the "statical friction," the "initial friction," and the "starting friction." It is seen, from Fig. 7, that a very slight increase in the velocity of rub-

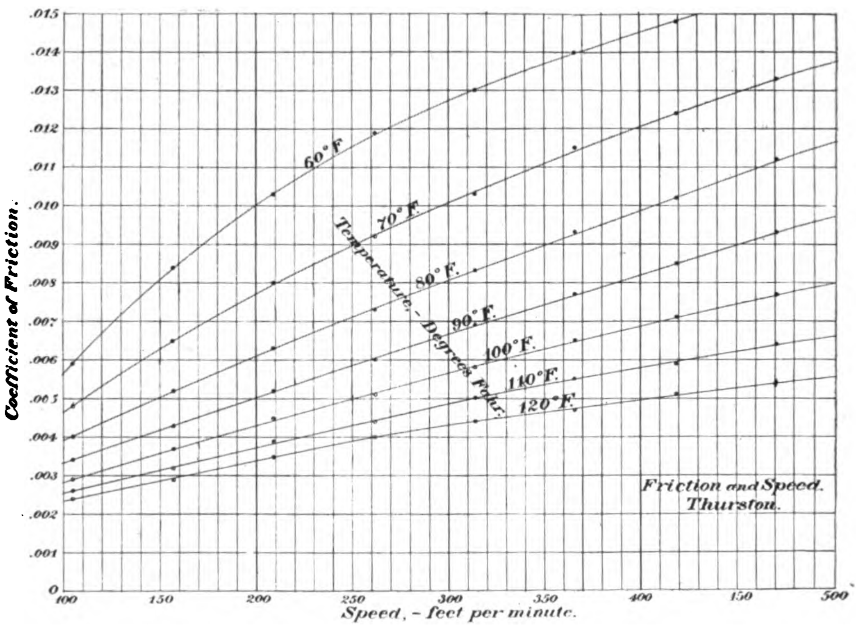


Fig. 8.

bing causes a great reduction in the coefficient of friction, especially when the bearing has a relatively high temperature. The coefficient of friction continues to diminish with further increase in velocity, reaching a minimum value at a certain critical velocity, which is relatively low, — somewhere between 100 and 200 feet per minute, for the cases shown in Fig. 7. This critical velocity point depends upon the lubricant, the bearing

pressure, and the temperature. Beyond the critical point the coefficient of friction increases slowly with the velocity of rubbing. The friction represented by this portion of the curve is sometimes termed the "running friction." Fig. 8 shows some curves of "running" friction plotted to a much larger scale.

It is important to note that the "starting friction" and the "running friction," in any given case, are affected in opposite manner by a difference of temperature. The higher the temperature the higher the starting friction and the lower the running friction. It is for this reason that the curves cross each other at or near their critical velocity points, in Fig. 7. This peculiar effect of temperature is probably related to the viscosity of the lubricant and the thickness of the lubricating film.

The analysis of these curves is simplified, if we bear in mind the observation, already noted, that lubricated journal friction is really a composite quantity, made up partly of sliding friction and partly of fluid friction.

The friction between the brake-shoes and the car wheels, when the brakes are applied, furnishes a ready example of pure sliding (unlubricated) friction. The celebrated train-braking experiments known as the Westinghouse-Galton tests, made in England, in 1878, furnished important information and valuable data regarding this kind of friction. (These experiments and the results and conclusions derived therefrom, form the basis of three important papers read by Captain Douglas Galton, before the Institution of Mechanical Engineers, in June and October, 1878, and April, 1879, on "The effect of Brakes upon Railway Trains.") Mr. R. A. Parke, who is the highest authority on the subject of train-braking, has given a complete résumé of the present state of our knowledge regarding braking friction, in a comprehensive article published in the Railroad Gazette, in 1901 (Vol. XXXIII) on "The Friction of Brake Shoes," and also in an exhaustive paper on "Railroad-car Braking," read before the American Institute of Electrical Engineers, Dec. 19, 1902. Mr. Parke has found, as the result of comprehensive study of various brake friction data, more especially the West-

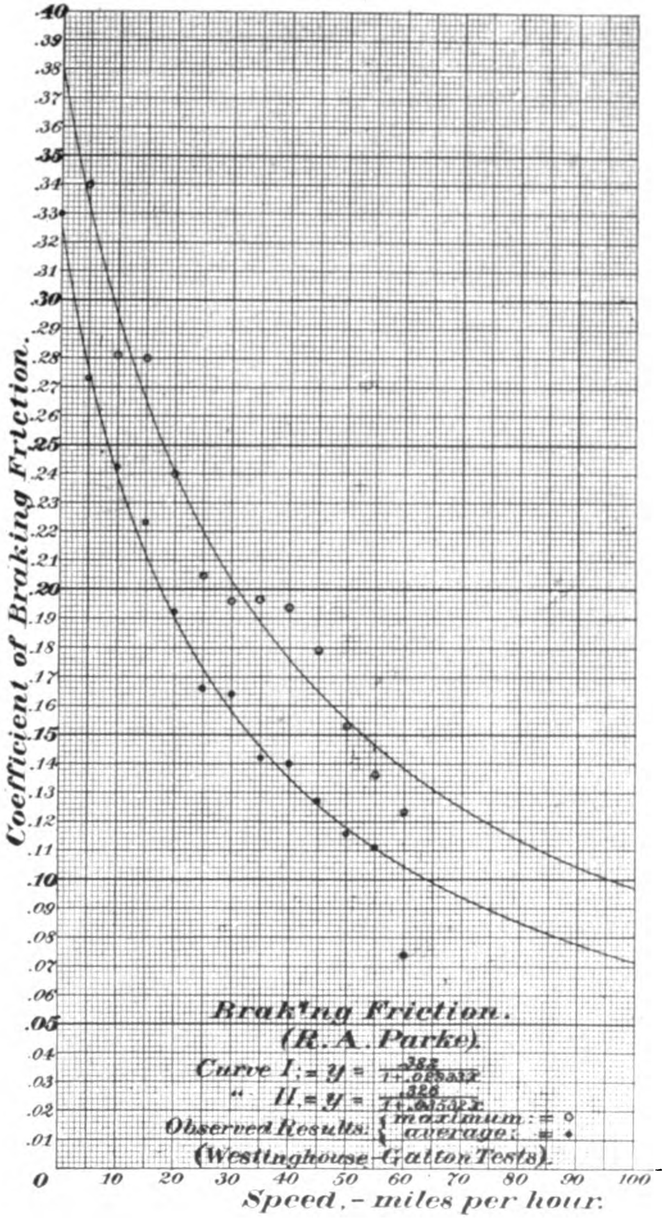

Coefficient of Braking Friction.
Speed, - miles per hour.
Brak'ng Friction.
(R. A. Parke).
Curve I; = y = .382
" II, = y = .326
Observed Results: maximum: = ○
average: = ◆
(Westinghouse-Galton Tests).
.40
.35
.30
.25
.20
.15
.10
.05
0
10
20
30
40
50
60
70
80
90
100

Fig. 9.

inghouse-Galton results, that the relation between the braking friction and train speed may be represented by curves of hyperbolic type; and he has derived two empirical formulae, one giving a curve of maximum values and the other giving a curve of mean values. These two curves and the corresponding formulae are reproduced in Fig. 9. The plotted points represent results actually obtained in the Westinghouse-Galton tests. It is seen that the lower curve agrees very closely with the mean of the observed results.

The other constituent of lubricated journal friction, namely fluid friction, is known to be an increasing function of the speed, which can be represented by a curve of parabolic type, passing through the origin of coordinates. The precise form of the curve will vary with the lubricant, the temperature, and other conditions.

We can now understand why the friction-speed curves have the general form shown in Fig. 7. At very low speeds the frictional effect due to pure sliding friction (Fig. 9) is very high, while the frictional effect due to fluid friction is practically negligible. At high speeds the sliding friction effect becomes relatively small, while the fluid friction effect becomes relatively large. The curve of journal friction, which is presumed to represent the superposition of these two effects upon each other, must, therefore, of necessity, have a minimum point between the two extremes (Fig. 7). The less viscous the lubricant, the smaller will be the fluid friction effect, and, consequently, the higher should be the "critical speed," or the speed at which the journal friction is lowest. We find, in Fig. 7, that the minimum point is actually farthest to the right for the curves which correspond to the highest temperature, *i. e.*, to the lowest viscosity.

The train resistance curves shown in Fig. 4 indicate clearly the relatively high train resistance found when starting and when running at very low velocity. This peculiarity is amply established by the results found in railroad practice, and also by numerous tests. The following abstract from the first paper (Feb., 1879) of Mr. A. M. Wellington before the American

Society of Civil Engineers, gives his conclusion regarding starting resistance, this conclusion being based upon elaborate "gravity," tests with freight cars, and careful experiments with specially constructed apparatus: —

"(2).— The initial resistance at the instant of starting is several times greater than this (*i. e.* than the axle and rolling friction) and greater for loaded than for empty cars, being at least 18 pounds per ton for loaded cars, and 14 pounds per ton for empty cars, as an average, but fluctuating considerably. Its amount probably varies with the length of the stop, according to some unknown law."

In Mr. Wellington's second paper (June, 1884), describing his "lathe" experiments (made in 1878), on friction at very low speeds, he gives, as conclusions based upon these experiments, values of (calculated) starting resistance which are higher still, ranging between 19 and 25 lbs. per ton. In his very complete observations, Mr. Wellington noted the interesting and important fact that the friction produced at very low journal speeds, *i. e.*, at the instant when motion begins, is "more nearly constant than any other element of friction, under varying conditions of lubrication, load and temperature." He found that the coefficient of "initial friction" varies from 0.09 to 0.12 for loads representing pressures on the bearings ranging between 30 and 280 lbs. per square inch; and he states that "within those limits, the coefficient was not greatly modified by load or by temperature." He also observed that the friction coefficient decreases slowly and regularly as the velocity of rubbing increases, and that the influence of temperature and of pressure then become more and more pronounced. Figure 10 is a reproduction of one of the diagram sheets of Mr. Wellington's paper, given in Appendix B of his work on "Railway Location."* In this diagram the two heavy line curves represent Mr. Wellington's (calculated) train resistance values for a loaded car; the two thin line curves indicate the corresponding value for an empty car; and the two dotted line curves (shorter

* The Cut is placed at the disposal of the Harvard Engineering Journal, by courtesy of Messrs. John Wiley & Sons, Publishers.

than the rest) indicate the corresponding values for a truck alone. In each case the upper line of the pair shows the train resistance values for a car with supposedly "hot" journals (120° to 150° F) while the lower line represents the values for a car with supposedly "cool" journals (under 100° F).

These higher results were, according to Mr. Wellington,

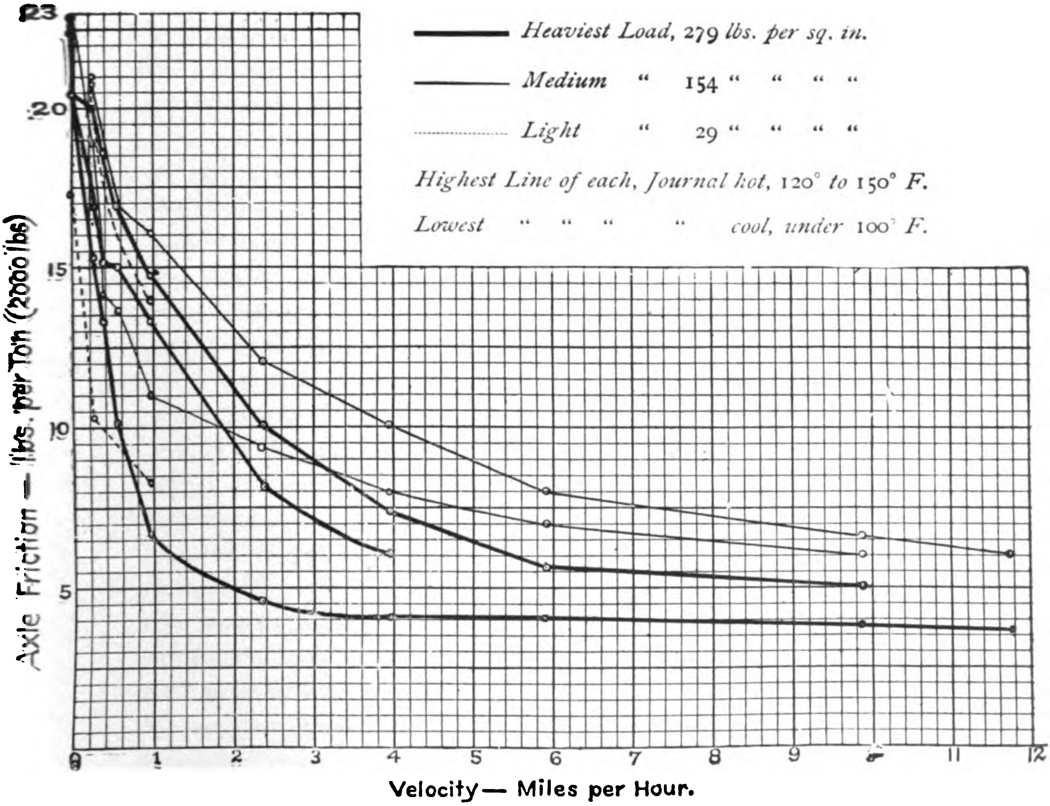


Fig. 10.

apparently confirmed by observations made "with some care at various times," by him, to ascertain the minimum "down" grade on which railroad cars, in ordinary service, can start themselves from rest. He found that the cars will "generally (but not always) start of themselves on a grade of 1.1 to 1.2 per cent,

indicating an "initial" friction of 20 to 24 lbs. per ton." He also refers to the experiments of Prof. Thurston, made with bearing pressures ranging between 50 and 300 lbs. per sq. inch, and gives the (calculated) initial train resistance indicated by these experiments, as follows: —

With sperm	oil lubrication,		14 lbs. to	28 lbs.	per ton.			
" lard	"	"	14 "	" 22 "	"	"		
" mineral	"	"	22 "	" 28 "	"	"		

Mr. Wellington also refers to results obtained by Prof. Kimball indicating values ranging between 22 and 31 lbs. per ton. He found the general average of all the results, including his own, to be 18 to 25 lbs., the general mean being 20.5 lbs. The correctness of this general mean seemed to him to be sufficiently well established inasmuch as a 1 per cent grade (corresponding to a traction force of 20 lbs. per ton) is, he states, "the lowest grade, by universal railroad experience, upon which cars can be relied on to start off from a state of rest with little or no assistance." Later observers have, however, found results which are considerably lower. According to Mr. J. F. A. Aspinall, the starting resistance, for English Freight Cars, may be taken at 17 lbs. per ton. According to Mr. A. C. Dennis (Fig. 4), the starting resistance is about 15 pounds per ton for (American) empty box cars, and only ten pounds per ton for loaded box cars, or less instead of more than for empty cars. This result for loaded box cars apparently contradicts the results of Mr. Wellington, and of Prof. Thurston (Fig. 6), and is also contrary to the result which might be expected from the considerations already given (*d*) regarding the influence of bearing pressure on the coefficients of starting and running friction. Additional tests and possibly further experimentation under definite, carefully noted conditions, are needed to throw light upon these discrepancies.

While it is clearly established, as the result of tests, that the train resistance rapidly falls to a minimum as the speed of the train increases, yet the exact speed at which this minimum occurs is still uncertain. According to Mr. Wellington, the "critical" speed corresponding to a minimum train resistance is

over 6 m. p. h. and may be as high as 10 to 15 m. p. h. The dotted line curve, in Fig. 4, representing Mr. Wellington's train resistance values for "loaded" cars, shows a minimum point occurring between 5 and 10 m. p. h., and the other curves, representing the results obtained by Mr. Dennis, show a minimum point between 15 and 20 m. p. h.

This discrepancy in the speed corresponding to minimum friction in the two cases, is, in all probability, due to a difference in some of the governing conditions. We are prepared to expect, from the considerations already given, that the critical speed will depend upon the bearing pressure, the lubricant and the temperature. It can readily be shown that it will also depend on the diameter of the journal and of the car wheels, since these dimensions determine the relation between the rubbing velocity at the bearing and the train velocity, in m. p. h. In the case of a car equipped with wheels 33 inches in diameter, and having journals $3\frac{3}{4}$ inches in diameter, each mile of linear travel of the car on the track will correspond to a rubbing motion between the journal and the bearing amounting to exactly 600 feet. It follows, therefore, that a linear velocity of the *train* equivalent to 1 m. p. h., corresponds to and causes a rubbing velocity, at the *bearing*, equal to 10 feet per minute

$$(i.\ e.\ \frac{600 \text{ ft.}}{60 \text{ min.}} = 10 \text{ ft. per min.}).$$

If we assume from the curves shown in Fig. 7 that the minimum friction occurs at rubbing velocities ranging between the limits of 100 and 200 feet per minute, we find, by a simple calculation, that the train speed corresponding to minimum journal friction would be between 10 and 20 m. p. h. for wheels and journals of the dimensions considered. (If we assume 150 feet per min. as the "critical rubbing velocity, the train speed corresponding to minimum journal friction would be 15 m. p. h.).

In Steam Railroad practice, while the diameter of car wheels is practically always 33 inches, the diameter of the journals increases with the maximum allowable load per axle. (Although 33 inches is the "standard" car wheel diameter for

both freight and passenger cars, yet larger diameters, up to 36 and even 39 inches are now being used, to some extent, for sleeping cars, parlor cars, private cars, etc., where more space is required under the car body, for various purposes.)

In Street Railway and Electric Railway practice, there is now a marked tendency to adopt and follow the "M. C. B." standards; and the standard wheel diameter, which was 26 inches in the "horse-car" days, became 30 inches later, when electric traction was introduced, and it is now 33 inches, except for the smaller electric cars. Wheel diameters of 36 inches and even 39 inches have been adopted in some cases, however, for high speed electric cars, requiring a greater power per ton, for rapid transit and suburban or interurban lines, this larger diameter being necessary in order to further increase the distance between the top of rails and the car floor, so as to make room for larger motors.

The limiting (maximum allowable) weight, per axle, for each of the four "M. C. B." types were given in Table I. According to the M. C. B. rules, an axle of the type A, having a journal diameter of 3.75 in., would be restricted to cars designed for a total maximum load not exceeding 15,000 lbs. per axle, or 7500 lbs. per journal bearing, which, for double-truck cars, having four axles, is equivalent to a maximum allowable total car weight of 60,000 lbs., including the load. The next larger size, Type B, having a journal diameter of 4.25 in., would serve for cars having a maximum load limit of 22,000 lbs. per axle (11000 lbs. per bearing), or 88,000 lbs., per car. The limits for types C and D as given in the table, correspond to maximum total car weights of 124,000 lbs. and 152,000 lbs. respectively.

Now, it is evident that for a wheel of the same diameter (say 33 in.) an axle journal of type B will have a greater rubbing velocity than one of type A, *at the same linear train travel.* Calculation shows that the rubbing motion at the bearing for a journal of 4.25 in. diameter (type B) will be increased from 600 to 680 feet per mile of linear travel of the car. Hence, the rubbing velocity will be 11.33 ft. per minute (instead of 10) when the train velocity is 1 m. p. h. and in the same proportion

at all other speeds. The following table gives the rubbing motion and rubbing velocity for all four types of "M. C. B." journals, for 33 in. wheels: —

TABLE II.

TYPE OF BEARING ("M. C. B.").	A	B	C	D
Diameter of Journal (inches)	3.75	4.25	5.0	5.5
Area of bearing, (square inches)	25.5	29.6	38 9	48.5
Mean Pressure on bearings with full load (lbs. per sq. in.)	294.	372.	398.	392.
Rubbing Motion (feet) per mile of car travel, (on 33″ wheels)	600.	680.	800.	880.
Rubbing motion, (in percent of train motion)	11.36%	12.88%	15.15%	16.67%
Ratio of rubbing to train velocity.	0.1136	0.1288	0.1515	0.1667
Rubbing velocity, (ft. per minute), corresponding to each 1. m. p. h. of train velocity	10.	11.33	13 33	14.66
Train Speed (m. p. h.), corresponding to rubbing velocity of 100 ft. per minute	10.	8.83	7.50	6.83
Do. for 200 ft. p. min	20.	17.66	15.	13.66
Average (= rubbing velocity of 150 ft. p. min.).	15.	13.24	11 25	10.24

It is evident from these figures that a change in the journal diameter would, of itself, account for a considerable difference in the critical speed. A change in the wheel diameter would, obviously, cause a difference, also; but in that case an increase in wheel diameter would have the same effect as a *reduction* in the journal diameter, since it would reduce the number of revolutions, and, consequently, the rubbing motion of the journal per mile of train travel. The rest of the difference in the critical speed may be accounted for by variations in some of the elements of train resistance which still have to be discussed.

It should be carefully noted that in calculating the portion of train resistance which corresponds to journal friction, it is necessary to take into consideration the fact that the surface (periphery) of the journal does not travel as fast as the car. We must distinguish between the ("tangential") effort which must be applied at the periphery of the *journal* and the ("trac-

tive") effort which must be applied to the car itself, in order to develop the power consumed by journal friction. In a moving car, assuming that there is no slip between the track and the wheels, the wheel periphery at the points of contact with the rails, moves at the same velocity and in the same direction as the *track*, the motion being kinematically equivalent to that which would be obtained if the car were stationary and the tracks were moving like an endless belt, at the given car velocity, but in the contrary direction. Hence it is clear that so for as the motion of the wheels and the power conveyed to the journal is concerned, a pulling effort applied to the *car* is the physical equivalent of a tangential effort or pull applied at the periphery of the *car wheels*. The corresponding tangential effort at the *journal* periphery, will obviously be one producing the same "*torque*." If we bear in mind the fact that torque is equal to the product of tangential effort by radius, we see that the tangential effort required for a given torque must vary inversely as the radial distance to the point at which the tangential force is applied; and that this effort is consequently greater at the journal bearing than at the periphery of the car wheel.

The tangential effort (T) at the journal bearing, is equal to the product of the pressure due to the weight (W) imposed on the bearing by the coefficient of friction (C), (*i. e.* $T = C\ W$). Denoting the radii of journal and car wheel by r and R, respectively, and the tangential effort at the wheel periphery by t, the torque will be $Rt = rT = rCW$, whence we have,

$$t = \frac{rT}{R} = \frac{r}{R}\ CW.$$

From the physical equivalence just noted, we see that the value of *t* will also represent the "tractive" effort, or the "force factor," (see p. 185, vol. II), of the power expended in overcoming the friction of the bearings).

It becomes evident, from these considerations, that, in order to obtain the value of the train resistance (*t*), due to the friction of the journal bearings, we must multiply the tangential effort (T) required at the journal periphery, by the ratio of the

radii, (r/R), or of the diameters, (d/D), of the journals and of the car-wheels. (The equations just given show this clearly.) This ratio which is, obviously, the same as the ratio of the "rubbing velocity to the "train" velocity, is given, in Table II, for all four "M C B" types of journals (for 33 inch wheels). It is now seen to be, in reality, the "correcting factor" by which allowance is to be made for the difference in the velocities of the train and of the journal periphery. It may also be, and is, more conveniently, regarded as *a factor modifying the coefficient of friction*, and giving its value in terms of a moving force applied, as it really is in this case, at the *wheel* periphery instead of the *journal* periphery. Thus, assuming the coefficient of friction to be $C = 0.008$, and the journal to be of type A, with 33 inch wheels,— for which the "ratio of velocities," as given in Table II, is 0.1136,— the "modified" coefficient would be $E = 0.008 \times 0.1136 = 0.000909$. This factor (E), multiplied by the weight on the journal bearings (in practice the whole car weight is usually taken), including the load, will give the tractive effort required to overcome the friction of the journal bearings. The tractive effort divided by the number of tons equals the train resistance per ton. Thus, for a double truck (4-axle) car, with journals of type A and weight limit of 60,000 lbs. ($W = 30$ tons), we would have, with the assumed value of C, a total tractive effort equal to

$$\begin{aligned} t = C\frac{r}{R} \times 30 \times 2{,}000 &= 0.008 \times 0.1136 \times 60{,}000 \\ &= 0.000909 \times 60{,}000 \\ &= 54.54 \text{ lbs.} \end{aligned}$$

and the corresponding train resistance, in lbs. per ton would be

$$f = C\frac{r}{R}\,W\;2000$$

$$f = \frac{C\;r\;2000}{R} \qquad (1)$$

$$= 0.000909 \times 2000$$

$$= 1.818 \text{ lbs. per ton.}$$

The value of f in equation 1, is not wholly independent of the car weight W, even though the symbol W does not appear

in that equation. It must be remembered that the coefficient of friction (C), is, as shown by Figs. 5 and 6, a function of the pressure on the bearings, which latter itself depends on the car weight. The maximum mean bearing pressures (equal to the total car weight, W, divided by the total area of all the bearings) to be expected for all four types of bearings, are given in Table II. Having determined, or else assumed, the bearing pressure, the friction co-efficient (C) corresponding to that pressure may be determined, either by means of an empirical formula, such as used for the curves shown in Fig. 5, or else by means of curves derived from actual tests, such as the curves shown in Fig. 6. The value of C assumed in the example given above was taken from Curve III, in Fig. 6, at the point corresponding to a pressure of 300 lbs. per square inch, which may be considered the limiting bearing pressure for journals of type A. The value obtained for f (= 1.82) may be said, therefore, to represent that portion of the total train resistance which is due to journal friction in the case of a fully loaded car having journals and bearings of type A, with 33 inch wheels, at or about the "critical" velocity. The preceding data and also the corresponding data for the other three "M C B" types of journals (for 33 inch wheels) are given in Table III.

TABLE III.

TYPE OF BEARING ("M. C. B.")	A	B	C	D
(Maximum) mean pressure on bearings (lbs. per sq. in.)	300	375	400	400
(Approximate) Coefficient of Friction (C), from Fig. 6, Curve III	.008	.007	.0065	.0065
$\frac{r}{R}$ (from Table II)	.1136	.1288	.1515	.1667
Train resistance due to journal friction (lbs. per ton) . . .	1.82	1.80	1.97	2.17

The figures in the last line indicate that the value of f is substantially the same (about 1.8 lbs.) for both types A and B,

about 0.2 lb. more for type C, and about 0.4 lb. more for type D.

It is interesting to note that Mr. Wellington's values for train resistance to be overcome when starting and when running at very low speeds (Fig. 10) were computed by the formula given in Equation 1. As he assumed the ratio $\frac{r}{R}$ to be = 0.1, the formula used by him took the following simple form:—

$f_s = C \frac{r}{R} 2000 = 200\ C$. Hence for values of C comprised between 0.09 and 0.12, it follows that f_s would have values ranging between 18 and 24 lbs. per ton.

(2) The friction due to the end-play of the car axle, is obviously, a form of journal friction. The end-play, itself, results from any cause which makes either the car body or the trucks oscillate, rock or swing. The principal causes are inequalities or variations in the track "level," in the track gauge and alignment; also the unequal yielding of the track at the joints; and centrifugal force, due to inertia, in going around curves.

The friction produced by end-play is of two kinds: First, the friction due to a file-like or rasp-like action between any inequalities, on the surface of the journal and bearing, such as ridges, grooves, scratches and flaws; second, the "end-thrust" friction due to contact under more or less pressure between the ends of the journal bearings and the axle collars or the wheel hubs. The "rasp" friction is probably negligibly small, when the journals and bearings are in good condition. With journals and bearings which are worn unevenly, in ridges and grooves, or which have rough surfaces, this friction may become important. Under normal conditions, this friction is probably more than offset, as an element of train resistance, by a decrease in the rotational friction which, it is well known, the end-play itself causes by improving the lubrication of the journal and bearing. The "end-thrust" friction has no such compensating features as the rasp friction. It apparently always operates so as to increase the train resistance. Our knowledge of its characteristics and its amount under different conditions is very

incomplete and imperfect. It is not unlikely that the train speed influences its amount to some extent, in any given case.

II. Unlubricated sliding friction. We are familiar with this form of friction, as manifested in the slipping of a belt on a pulley, or the slipping of a brakeshoe on a car wheel. Another interesting example of it is the slipping of the wheels of a locomotive on the track under certain conditions, such as when starting a heavy load on a slippery track. Some of the characteristics of this kind of friction have already been noted (see Fig. 9).

(3) A certain amount of slip may occur at times, between the car wheels and the track, owing to various causes, including: —

(a) The lubrication of the rails by water, snow, ice, mud, dirt, grease, grit, rust, or any foreign substance.

(b) Excess of tractive effort applied to the driving wheels, such as in attempting to accelerate quickly, when starting.

(c) Insufficient adhesion of driving wheels.

(d) Jumping or skipping of driven wheels in consequence of low points of the track, oscillation of the car, etc.

(e) Track curves, when the car wheels are not properly "coned."

(f) "Skidding" of wheels on the track, when the brakeshoe pressure is excessive.

(g) "Flat spots," or like defects, on car wheels, due to skidding, or to unequal wear.

In some of these cases of "rail" friction, notably (a) and (d), the slipping tends, perhaps of itself, to reduce the train resistance slightly. Unfortunately, the loss of adhesion between the car wheels and the track, which accompanies this slipping, presents, in other respects, such serious disadvantages (c. d. f.) as to render slipping very objectionable in these cases. The maximum power which can be applied to a given car or train, when starting and accelerating, and the maximum brakeshoe pressure allowable when stopping (or the *accelerating* force and the *retarding* force allowable), are both limited by the "adhesion" between the car wheels and the track. This means that quick starts and quick stops cannot be made unless the adhesion is sufficient to prevent

"slipping" between the car wheels and the rails when starting, and to prevent "skidding" between them, when stopping. Hence, "rail" friction is a matter of as much importance as train resistance, in the study of train movement; and, without attempting a comprehensive discussion of it, here, a short digression will be made for the purpose of pointing out some of its important characteristics.

The "coefficient of adhesion," which might properly be called the "coefficient of rail-friction," is, as you should know, a figure expressing the ratio between the force tending to cause the car wheels to slip on the rails, and the pressure exerted on the surfaces in contact. Thus a coefficient value of 0.20 means that it would take a force equal to at least 20 per cent of the total pressure exerted on the rail by the wheel to cause that wheel to slip or to skid. It is admitted, generally, that the values of this coefficient vary with the condition of the track, but the variation is erratic, — showing wide discrepancies under apparently the same conditions, — and it is impossible to attempt more than a merely rough approximate comparison.

(The adhesion being obviously equal to the tangential effort required at the wheel periphery to cause it to slip, is measured by the product of the weight on the wheels and the coefficient of friction.)

All authorities agree that the highest coefficient of adhesion is obtained with rails which are bright, clean, and dry, and that values successively lower are obtained with rails which are damp, or wet, greasy, sleety, or rusty. Table IV contains various values of the coefficient of rail-friction, which give an idea of its variation. The figures in the first column are computed from data given in "Molesworth's Pocket-book"; those in the second column are from the Galton-Westinghouse tests; those in the third column are from tests made on the "P. L. M." Railroad, in France; those in the fourth column are general, approximative figures, gathered from various sources, and used by many engineers for rough calculations.

TABLE IV.

CONDITION OF RAILS.	COEFFICIENT OF RAIL-FRICTION ACCORDING TO			
	Molesworth	Galton	P. L. M.	
Clean, very dry . . .	0.273	.19 to .35	.187 to .246	.25 to .28
" " " (average)		.25		
" " " (with sand)		.20 to .40		.30
Clean, dry	.204			
Damp			.144 to .208	
Wet	.241	.18		.20 to .25
Very wet	.250			.25
Wet, with sand . . .				.25
Greasy	.136			.14 to .15
" (with sand) . .				.20
Frosty or sleety . . .	.091			.10 to .15
Rusty			.136 to .201	?
" (with sand) . .				.10 to .15

The figures given in this table are all subject to caution. This is particularly true in the case of damp, wet, greasy, sleety, and rusty rails, where a relatively slight change in the degree of dampness, etc., makes a material difference in the adhesion. Additional tests and data are greatly needed to determine and to fix the values of these coefficients more precisely. With regard to the effect of sand, it is not now believed that it increases the adhesion very much, if at all, on a track which is in very good condition, although it is unquestionably of utility on a track which is in bad condition, — damp, wet, greasy, etc., — by increasing the adhesion to substantially that of a dry, clean rail.

It is to be expected, from the form of the curves shown in Figs. 5 and 6, that the adhesion between the rail and the wheel tread will vary (inversely) with the "pressure density" at the points of contact. This contact is, theoretically a *line*, and, practically, a *surface*, — somewhat pear-shaped, — whose area depends on : —

(a) The elasticity, and the consequent yielding (compression), of the materials of the rails and of the wheel-tires.

(b) The diameter of the car-wheels.

(c) The form, — especially the width, — of the rail-head.

The effect of the first variable (a), is illustrated by the difference in adhesion found with wheels whose treads are of steel and those whose treads are of chilled cast iron. The effect of the second variable (b), is apparent from geometrical considerations. The effect of the third variable (c), has been noted by Dr. P. H. Dudley, who finds that the coefficient of rail-friction increases with the width of the rail-head.

It is conclusively established by many observations, notably by the tests made in France by M. Poiree, and by the Galton-Westinghouse tests, made in England, that the coefficient of adhesion (or rail-friction) diminishes rapidly as the "rubbing velocity" increases. (The law of variation, for the Galton-Westinghouse tests is shown in Fig. 9.)

(4) Wheel-flange friction is a grinding action occurring between the flange of a car-wheel and any object against which it is pressed, — usually the side of the rail-head. There is always more or less frictional contact between the wheel flanges and the rails, — first at one side, then at the other side, of the track. It is believed that the wheel-flange friction is greater with pivoted trucks than with rigid trucks, owing to their oscillation. It has been proposed to reduce this friction by pivoting the truck ahead of its center; but the fact that such trucks would not work equally well in both directions is an insuperable objection in most cases. A side wind tends to force the train bodily to one side and to increase the flange friction on that side of the track. In going around curves each wheel is usually forced against one rail or the other so as to make the grinding action more or less constant against that rail.

In the case of "tee" rails the grinding action is against the inside of the rail-head only. On a straight track, well built and in good condition, the wheel-flange friction, it is believed, tends to diminish as the train velocity increases. This may be because the wheels, when the train velocity increases, do not so often shift their position from one side of the track to the other, and the flanges have fewer contacts with the rail-head on either side of the track.

In the case of "grooved" rails the grinding action is a more

complicated and a more serious matter. It involves both sides and the periphery of each wheel-flange. In addition to the friction against the sides of the groove there is friction against the dust, dirt, etc., which is always to be found in the groove, sometimes even to an extent such that the car weight rests upon the flange as much as, or more than, upon the tread of the wheel. It is obvious that the flange, having a diameter greater than the wheel-tread, will have a higher peripheral speed than the tread, and, consequently, will have a slight "slip" with respect to the bottom and the sides of the groove. The dirt in the groove will therefore act somewhat like a brake-shoe applied to the wheel-flange. Wheel-flange friction is a very important element of train resistance in street railway work, because grooved rails are so generally used in the cities.

Braking Friction. This kind of friction is also a form of unlubricated sliding friction; and although it does not constitute a part of the train resistance while the train is running with the brakes "off," it becomes a supplement thereto, — an artificial train resistance, so to speak, — when the brakes are applied. It is of great interest and importance, not only on account of its relation to the stopping of trains safely and quickly, but also on account of the great energy losses which it causes. It represents the "force-factor" (p. 184, Vol. II) of a quantity of energy which is wasted and lost, purposely, so to speak; and, unfortunately, this quantity of energy is a very large percentage (50 per cent or more) of the whole energy applied to a car or train.

The complete analysis of the characteristics of braking-friction brings into consideration all of the laws and properties of unlubricated sliding friction which have already been referred to, and many others, some of which, — for instance, the effect of the heat developed in the brake-shoes in modifying the coefficient of friction, — are, as yet, known and understood only imperfectly.

The three papers of Capt. D. Dalton, and the articles and the paper of Mr. R. A. Parke, already mentioned, are the best sources of information and data available on the subject at the present time.

The relation between the braking friction and the track adhesion becomes a very important matter, in all cases where it is desirable to make quick stops. The well known fact that the maximum brake-shoe pressure allowable in braking is limited by the adhesion of the wheels upon the track was noted in the very first paper of Capt. Dalton. The following quotation from this paper is of interest in this connection: "In order to obtain the maximum retarding power on the train, the wheels ought never to skid; but the pressure of the brake-blocks on the wheels ought just to stop short of the skidding point. In order that this may be the case, the pressure between the blocks and the wheels ought to be very great when the brakes are first applied, and ought gradually to diminish until the train comes to rest."

If the brake-shoe pressure be allowed to exceed a certain limit, the wheels will begin to slip on the track and, in nearly all cases, they will almost immediately "skid," or slide upon the track without turning. The explanation of this phenomenon is quite simple when we consider the effect of the "rubbing velocity" on the coefficient of sliding friction, as exhibited in Fig. 9. (The curves of rail-friction are presumably of the same general form as the curves of braking friction, and, for bright clean dry rails, the coefficient values are probably very near those indicated by the curves, being possibly a little lower; for other conditions of rails, the values are of course materially lower, as might be expected from the data in Table IV.) So long as the wheels do not slip, the rubbing velocity between the track and the wheel-treads is zero, and the rail-friction or "adhesion" has its highest value. When the wheels slip on the rails, however, there is a rubbing velocity between the wheel-tread and the rails; and, as the curves in Fig. 9 clearly show, the coefficient of friction will diminish more and more as the rubbing velocity increases. For example, if the law of variation be approximately as shown by the lower curve in Fig. 9, the coefficient of rail-friction will have decreased to one half its initial value when the rubbing velocity due to slipping has increased to about 28 m. p. h. A train running at this

speed with its wheels "locked" by the brakes and skidding on the rails, would have, therefore, only about half the "adhesion" which it had before the brake-shoes were applied and the wheels began to slip.

At the time that the brakes are applied the rubbing velocity between the brake-shoes and the wheel-treads is as high as the train speed, and, consequently, the braking friction is relatively low, for any given pressure; but as the train speed becomes reduced and the rubbing velocity at the brake shoes diminishes, the braking friction will increase, according to the law shown in Fig. 9. We can readily understand, now, the effect of an excessive pressure on the brake-shoes, such for instance as will cause the wheels to slip even slightly. The slightest slip causes the rail friction to diminish and, at the same time, the braking-friction to increase, the result being that the wheels are quickly brought to a stop and caused to skid, unless the brake-shoe pressure is diminished. It is obvious, from what precedes, that if "skidding" is to be obviated (which is necessary in making quick stops) the braking friction (= brake-shoe pressure × coefficient of braking-friction) must never, at any time, exceed the adhesion (= pressure on wheels × coefficient of rail friction.) This means that in order to stop a train quickly, the "adhesion" of the track must either be naturally very good, or else means must be resorted to, such as by using sand, to increase the coefficient of rail-friction. On a greasy track the "adhesion," without sand (see Table IV) would probably not exceed 300 lbs. per ton (= 0.15 × 2000); and the braking friction ought to be somewhat less. On a greasy track, when sand is used, the adhesion would be at least 400 lbs. per ton (= 0.20 × 2000); and the braking-friction could be increased to nearly that amount. The following quotation from the A. I. E. E. paper of Mr. R. A. Parke is the most authoritative statement on this subject:

"If sand be suitably provided whenever the condition of the rail requires it, the coefficient of rail-friction always available (unless perhaps in the case of rail roads running in streets) is at least .20 and may doubtless be safely regarded, in at least

all cases where emergency calls for the highest efficiency, as .25 of the pressure of the wheel upon the rail. A brake system of ideal efficiency in the time of necessity is thus one in which the brake-shoes are so applied to the wheels that a retarding rail-friction equal to one fourth the weight of the train is instantly realized and continuously maintained throughout the stop."

It is worth while noting that the braking-friction at any given wheel represents the "force factor" of the energy dissipated at that wheel by friction, the said energy being equal to the distance-integral of that force-factor taken over the distance covered in making the stop.

(*To be continued.*)

THE HARVARD TELEPHONE SYSTEM.

E. A. STEVENS, JR., 1904.

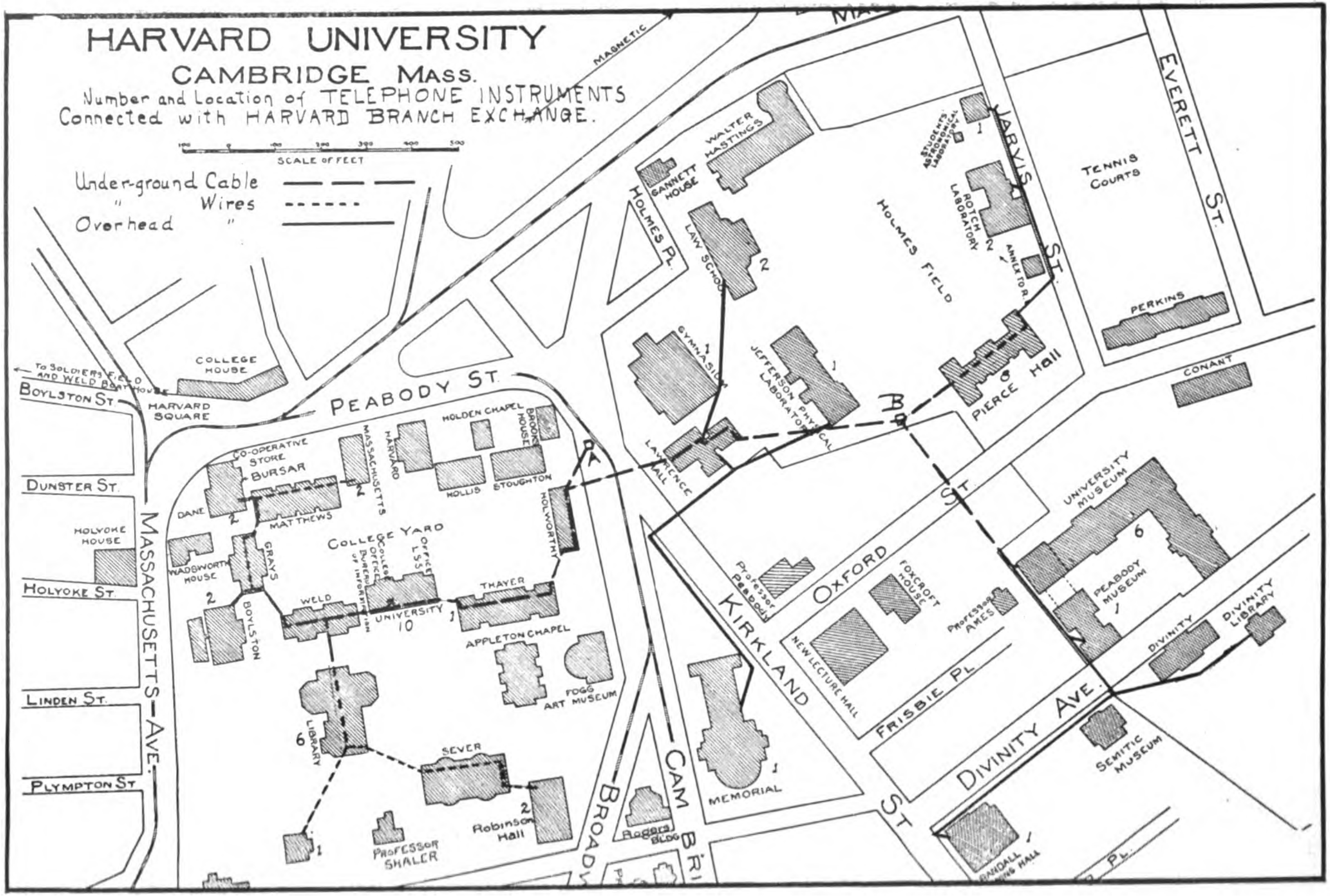
DURING the summer of 1902 the present telephone system was installed here at Harvard. This system embraces fifty-one telephone instruments located in nineteen University buildings connected by underground cable and aerial wires to a branch exchange situated in University Hall. This branch is connected with the Cambridge Exchange by seven trunk lines.

The instruments themselves are the ordinary Bell receiver and transmitter, hung in most cases on a swinging arm fastened to the side of the subscriber's desk. For the rental of each of these telephone sets the subscriber pays the New England Telephone and Telegraph Co. twelve dollars per year, and in addition to this he has to pay five cents for each call outside the Harvard Exchange.

To connect the subscribers' instruments to the exchange both overhead wires and underground cables are used. The overhead wires are used as little as possible, being strung in places where they would be out of sight, where there are but one or two pairs of conductors, or where underground construction would be an unreasonable expense. These wires are copper conductors covered with braided, water proof insulation and twisted in pairs. If there are several over-head wires to be run together, as between the Law School and Lawrence Hall, there is first strung a messenger wire which is an ordinary steel stranded wire and better able to stand strains than the copper wires. The bundle of conductors is then fastened at intervals of about two feet to this steel messenger wire. Under-ground construction is used, with the exception of a short length between Boylston and Grays, throughout the yard. The cables consist of several pairs of rubber insulated, twisted copper conductors, No. 18 B. & S., surrounded by a lead sheath. These cables are run, wherever possible, in the steam tunnels and through the basements of the buildings, no attempt having been

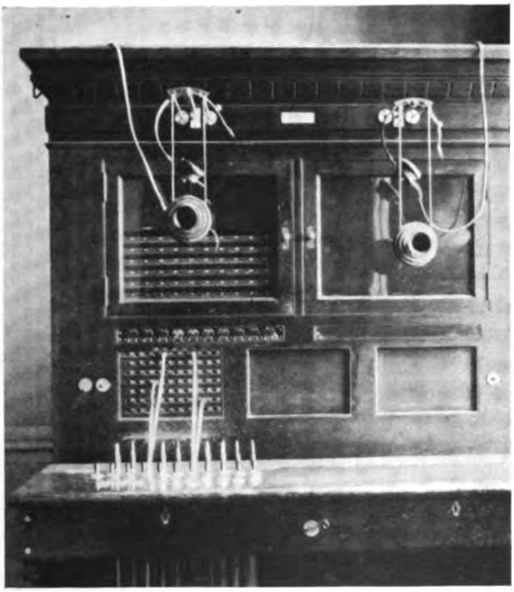
made to protect them. Elsewhere the cable is laid in conduit consisting of a single line of iron pipe laid in the earth from one to three feet below the surface. This pipe is three inches in diameter and is put down in sections about twelve feet long. At each joint is wedged an iron sleeve around which is packed cement to keep out moisture and help keep the pipe in line when the ground freezes and thaws. All of the cable and conduit work was done by the University and is not the property of the Telephone Company. In many cases, however, the Telephone Company has been given the use of wires in these cables for connecting the pay stations which are scattered throughout the University buildings. The wires from these pay stations are not connected with the Harvard Exchange but go directly to the Cambridge Exchange. If a branch occurs in this underground line the junction is made, wherever feasible, in the basement of one of the buildings; here the larger cable divides, and two or more smaller cables go out in their respective directions. In all of the cable work larger cables have been laid than are at present absolutely necessary, thus giving plenty of room for growth without extra expense.

From the distributing frame at the exchange in University Hall three cables branch out; one of thirty pairs goes (see map) through the steam tunnel to Weld, and one of thirty pairs and another of fifteen pairs go in the opposite direction to Thayer, also through a steam tunnel. In the basement of Weld the main cable branches, one arm of fifteen pairs going through the steam tunnel to the Library and another of fifteen pairs going through a steam tunnel to Grays where it ends in a cable terminal box. In such a box each wire is soldered to a separate lug and connected by fuses to other lugs to which can be fastened over-head wires or wires of another cable. From this terminal-box in Grays some dozen pairs of wires are run. Two go overhead to Boylston, several supply pay stations in Grays and the others run through the steam tunnel to the basement of Matthews, where they in turn divide, following steam tunnels to Dane and to Massachusetts respectively. The fifteen pair cable which goes from Weld to the Library ends at the latter


HARVARD UNIVERSITY
CAMBRIDGE MASS.
Number and Location of TELEPHONE INSTRUMENTS
Connected with HARVARD BRANCH EXCHANGE.
SCALE OF FEET
Under-ground Cable
" Wires
Overhead "
MAGNETIC
EVERETT ST.
JARVIS ST.
TENNIS COURTS
PERKINS
CONANT
HOLMES FIELD
ROTCH LABORATORY
ANNEX TO R.
STUDENTS' ASTRONOMICAL LABORATORY
WALTER HASTINGS
GANNETT HOUSE
HOLMES PL.
LAW SCHOOL
GYMNASIUM
JEFFERSON PHYSICAL LABORATORY
LAWRENCE HALL
PIERCE Hall
UNIVERSITY MUSEUM
PEABODY MUSEUM
DIVINITY
DIVINITY LIBRARY
SEMITIC MUSEUM
DIVINITY AVE.
RANDALL HALL
Professor AMES
FOXCROFT HOUSE
OXFORD ST
NEW LECTURE HALL
FRISBIE PL
Professor Peabody
KIRKLAND ST
MEMORIAL
CAMBRIDGE
BROADWAY
Rogers BLDG
PEABODY ST.
HARVARD SQUARE
COLLEGE HOUSE
To SOLDIERS FIELD AND WELD BOAT HOUSE
BOYLSTON ST.
DUNSTER ST.
HOLYOKE HOUSE
HOLYOKE ST.
LINDEN ST.
PLYMPTON ST
MASSACHUSETTS-AVE.
CO-OPERATIVE STORE
BURSAR
DANE
MATTHEWS
MASSACHUSETTS
HARVARD
HOLDEN CHAPEL
BROOKS HOUSE
HOLLIS
STOUGHTON
HOLWORTHY
COLLEGE YARD
OFFICE L.S.S.
COLLEGE OFFICE BUREAU OF INFORMATION
WADSWORTH HOUSE
GRAYS
BOYLSTON
WELD
UNIVERSITY
THAYER
APPLETON CHAPEL
FOGG ART MUSEUM
LIBRARY
SEVER
Robinson Hall
PROFESSOR SHALER

place in a terminal box, and there are connected to this the instruments used in the Library, the conduit line to President Eliot's, and the line through conduit, the basement of Sever and the steam tunnel to Robinson Hall.

The two cables which run from University to Thayer continue on through the basement of Thayer, the steam tunnel to Holworthy and the basement of Holworthy. One of these cables contains the seven trunk lines which connect the Harvard



HARVARD TELEPHONE SWITCHBOARD.

and the Cambridge Exchanges, the wires which supply all the direct current used in the system and the wires for most of the pay stations in the yard. From the basement of Holworthy a thirty pair cable is laid in conduit to a manhole, located in the street, at A on the map, where it connects with the cable running to the Cambridge Exchange. The other cable runs through conduit under the street to the basement of Lawrence Hall and here branches, one arm of thirty pairs continuing on through conduit towards Pierce, and the other arm of ten pairs

ending in a terminal box. From this terminal box go out an overhead line of five pairs to the Gymnasium and the Law School, one line to Jefferson Physical Laboratory, and one through the trees on the north side of the delta to Memorial. Between Pierce and Jefferson, at B on the map, is a shallow manhole some two feet square. Here the thirty pair cable from Lawrence Hall branches into two fifteen pair cables, one of which goes to Pierce Hall, and the other to a terminal box on a pole near the University Museum. From this pole over-head wires go to the University and Peabody Museums, Divinity Library and Randall Hall. From Pierce Hall an over-head line extends to the Mining Building and on to the Astronomical Laboratory.

The switchboard, as seen in the illustration, is a two position board with an ultimate capacity of two hundred and twenty subscribers' lines and twenty trunk lines. The present equipment of the board is sixty subscribers' lines and ten trunk lines; and of these only forty-nine subscribers' lines and seven trunk lines are in use at the present time. At the upper part of the board, behind a glass door are the subscribers' drops, a shutter on which rises as soon as a subscriber removes his receiver from the hook, thus notifying the operator that someone is calling. Just below these drops are the trunk line drops which fall when the operator at the Cambridge exchange rings through them. Below these trunk line drops are seven strips of jacks, ten jacks to a strip. Each of these jacks is a socket containing the two terminals of a line and in some cases has, in addition to one contact for each side of the line, switching apparatus and another contact for working signals. Switchboard cables from these jacks run to the distributing frame back of the switchboard and are cross-connected to the underground cables. As each of these jacks represents the terminals of a line, in order to connect two lines it is necessary only to have a flexible connection of some sort at the ends of which are plugs which can be inserted in the respective jacks. On the board there are at present ten pairs of these plugs, and any pair can be used to make a desired connection.

On each plug are three contacts termed the tip, the ring and the sleeve. The tip and the ring are the talking contacts, and the sleeve a signalling contact. Each pair of these plugs is connected to a key and combination of contacts in such a manner that when the handle of the key, seen on the face of the board in the illustration, is thrown from the operator the operator's telephone set is in connection with both of the plugs of the pair or with both subscribers if the plugs are inserted in subscribers' jacks. When this handle is thrown towards the operator, ringing current can be sent from a hand magneto to the front or calling plug of the pair, and any subscriber can be called if the plug is inserted in the proper jack. When this handle is in its normal or upright position the operator's telephone set is cut out, the plugs are connected and a means provided for supplying battery to each of the plugs. This battery is supplied only when connection is made between two subscribers' lines. When connection is made with a trunk line battery is supplied over that line at the Cambridge exchange. All the power, except the ringing current, used at the Harvard Exchange is supplied from the regular storage battery at the Cambridge Exchange and comes in the same cable with the trunk lines, two wires of a twisted pair being used in multiple for each side of the line to obtain greater conductivity. One side of the battery is grounded, and the two sides of the line are called "battery" and "ground" respectively. Although in the "diagram of circuits" several batteries are represented, this is only for clearness; actually only one battery of twenty-four volts is used for all purposes including signalling and talking.

When a subscriber removes his receiver from the hook, the comparatively low resistance of the receiver and transmitter is substituted for the high resistance winding of the bell electromagnet, and consequently enough current is allowed to pass through the circuit from the battery, A (see diagram of circuits) to energize the electromagnet of the subscriber's drop, B, and cause it to attract its armature and thus raise the shutter. On this shutter is a number which corresponds with the number

on the jack, C. As soon as the operator sees that this shutter is up, she inserts in the jack any one of the back row of plugs, as Q, which is not in use. This operation opens the circuit of the drop, B — thus allowing the shutter to fall — and supplies the line with current from the battery through the contacts of the relay, E, and the retardation coil, F. This retardation coil consists of two coils of wire wound on a closed magnetic

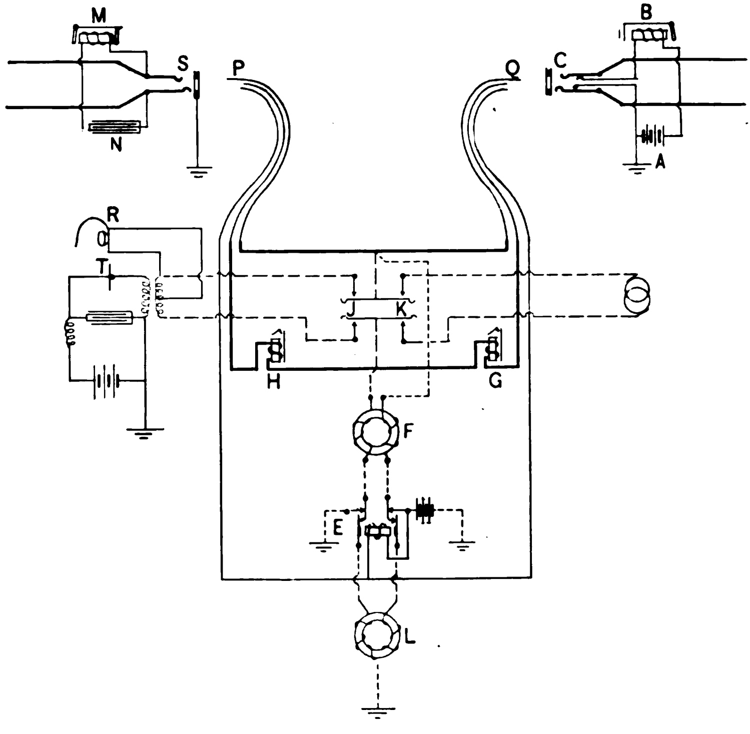


DIAGRAM OF CIRCUITS — HARVARD TELEPHONE SWITCHBOARD.

circuit and prevents cross-talk between two lines using the same battery. By reason of its highly inductive qualities it shuts out the high frequency talking currents, but allows the whole system to be fed with direct current from the same battery. The signal, G, being in circuit is operated and stays at "busy" until the subscriber's receiver is hung up. Having

"plugged in," the operator presses backward the key immediately in front of the plug used and thus makes the contacts at J and connects her receiver, R, and transmitter, T, with the line. As soon as she ascertains the person wanted, she inserts the front plug, P, of the pair selected in the jack of the subscriber to be called, throws forward the key — making the contacts at K — and turns the handle of the magneto which rings the subscriber's bell. Throwing the key forward not only makes the contacts at K but also cuts from the circuit the plug, Q, and allows ringing current to be sent only on the front plug, P. This is not shown in the wiring diagram. As soon as the subscriber answers, current flows through the signal, H, and thus shows the operator that her part in making the call is at an end. Should either person now wish to call the operator, he must work his receiver hook up and down. This will cause the busy signal connected with his line to rise and fall, and the operator will press the listening key backward and communicate with the subscriber. A call for a Cambridge or out of town number is treated similarly, with the exception that the operator plugs into a trunk line jack, S. This lights a small electric lamp at the Cambridge Exchange and thus notifies the Cambridge operator that some one is calling; it also brings into play the third contact of the jack and the sleeve of the plug by allowing current to flow from battery through the winding of the relay, E, the sleeve of the plug, P, and on to ground through the third contact of the jack. This current energizes the relay, E, thus cutting off battery from the line and grounding the two sides of the line through the retardation coils, F and L. Talking current is then supplied at the Cambridge exchange. In order that the Cambridge operator may call up at any time the Harvard operator, whether or not a plug is left in a jack, the drop, M, is not cut out by the insertion of a plug. If the drop alone were thus left shunted across the line much direct current would leak through it and would not go on to supply the station beyond. To prevent this a condenser, N, is put in series with the drop, thus presenting a free path to the ringing or alternating current, but entirely shutting off the direct current.

The operator's telephone set is connected to each of the ten listening keys by a pair of wires which runs to each of them in common. Only one of these keys should be thrown at a time; if two are thrown the two lines will each be connected to a single pair of wires and will therefore be crossed. This is sometimes taken advantage of if several subscribers desire to be connected at the same time. For instance: suppose four different subscribers, A, B, C, and D, desire to hold a consultation; A and B are connected in the usual manner, also C and D, then the four are connected by throwing forward the two listening keys which connects each line to a common pair of wires. Conversation can then be carried on between all four. This, however, should not be done, as all "traffic" is tied up unless the operator interrupts the conversation or cuts off one of the subscribers.

There is an operator at the Harvard Exchange only from 8 A. M. to 5.15 P. M., therefore some means must be provided by which a subscriber can be connected with the Cambridge Exchange at other hours. At one side of the switch board are seven or eight pairs of metal strips. To each pair of strips are connected through long flexible cords, four plugs, each having two contacts — the tip and the ring — one connected to each strip. One of these plugs can be inserted in a trunk line jack and each of the other three in subscribers' jacks, thus making a three party line and putting each subscriber in direct connection with the Cambridge Exchange. Since there are but seven trunk lines, it is obvious that only twenty one subscribers can be connected in this manner over night on the present three-party-line basis.

During the month of January, there were handled in this office an average of two hundred and one calls every day the office was open. Of these about twenty-five per cent were purely local; thirty-three per cent in-coming calls — calls from other exchanges to the Harvard Exchange — and the remainder, or forty-two per cent, outgoing calls.

The two chief reasons for installing this branch exchange were to obtain cheaper and more efficient service for the University;

cheaper because of the large number of purely local calls handled without additional expense; more efficient because of the comparatively few calls to be handled by one operator. Both of these results have been obtained, and the service is as satisfactory as that of any manually operated exchange can be.

HITCHIN, HERTFORDSHIRE.

BY W. S. PARKER, '99.

HAVE you ever been to Hitchin? It is a question I have put to every lover of England with whom I have traded in foreign experiences and with only one exception, the sad answer "No" has been returned. And the negative has generally been accompanied by "Where is it?" They not only have never walked its charming streets but have never even heard of it. It is thus that one is forced to realize again that the world is wide and that fate does not lead everyone to the same Garden of Eden.

How fortunate this is! What a joy it gives us when chance leads us down a quiet lane where no other explorer treads, at least for the present, to joggle us with his inquisitive elbow and jar us with inane questions; where we can rest peaceful in the enjoyment of this new experience, which, like a play, with endless scenery and perfect actors, is being performed for our own special benefit. What a joy it is, I say, in comparison with that wild scramble for impressions in some great Rome where all the roads of chance seem to converge, under the special supervision of the all powerful Cook. It was in that way I twice visited Hitchin, doubly blessed with the guidance of a favored dweller in my new Garden of Eden, who with a more practiced eye and wider knowledge could aid me to a fuller appreciation of its many delights.

It is of modern Hitchin that I wish to write, but a few words of its past will be of interest. It seems to have taken its name from the near by wood called "Hitch" which once was much larger, extending probably to the town. The Saxons called it "Hicce," and Edward the Confessor in denoting it to Earl Harold called it "Hitche." Some, however, assert that the name is derived from the little River Hiz which flows near by.

In 1881, evidences of Roman civilization were discovered not far from Hitchin in the Parish of Great Wymondley, when

several Roman urns containing ashes were dug up; and in 1884, various coins and the tessellated pavement of a Roman villa were discovered at "Nine Springs."

Hitchin was in the possession of the Crown till Edward the Confessor granted it to Earl Harold, on whose death, at the Battle of Hastings, it reverted to the Crown and William the Conqueror. The manor of Hitchin was a favorite gift of the English kings and was many times granted and as often regained by the Crown. Henry VIII granted it for life successively to his queens Katharine of Aragon, Ann Boleyn and Jane Seymour, and, as history notes, in rather rapid succession. They were not allowed to enjoy the privileges of its possession for long.

Hitchin was, in 1525, according to Stowe in his chronicles, the scene of a narrow escape of the much-married Henry who, while following his hawk, was leaping a ditch with a pole, when the pole broke. If a footman had not leaped into the water and pulled him out, he doubtless would have been drowned, his head having stuck fast in the clay. Thus Hitchin was deprived of the honor of making history and Henry was permitted to live to mar it with his later atrocities.

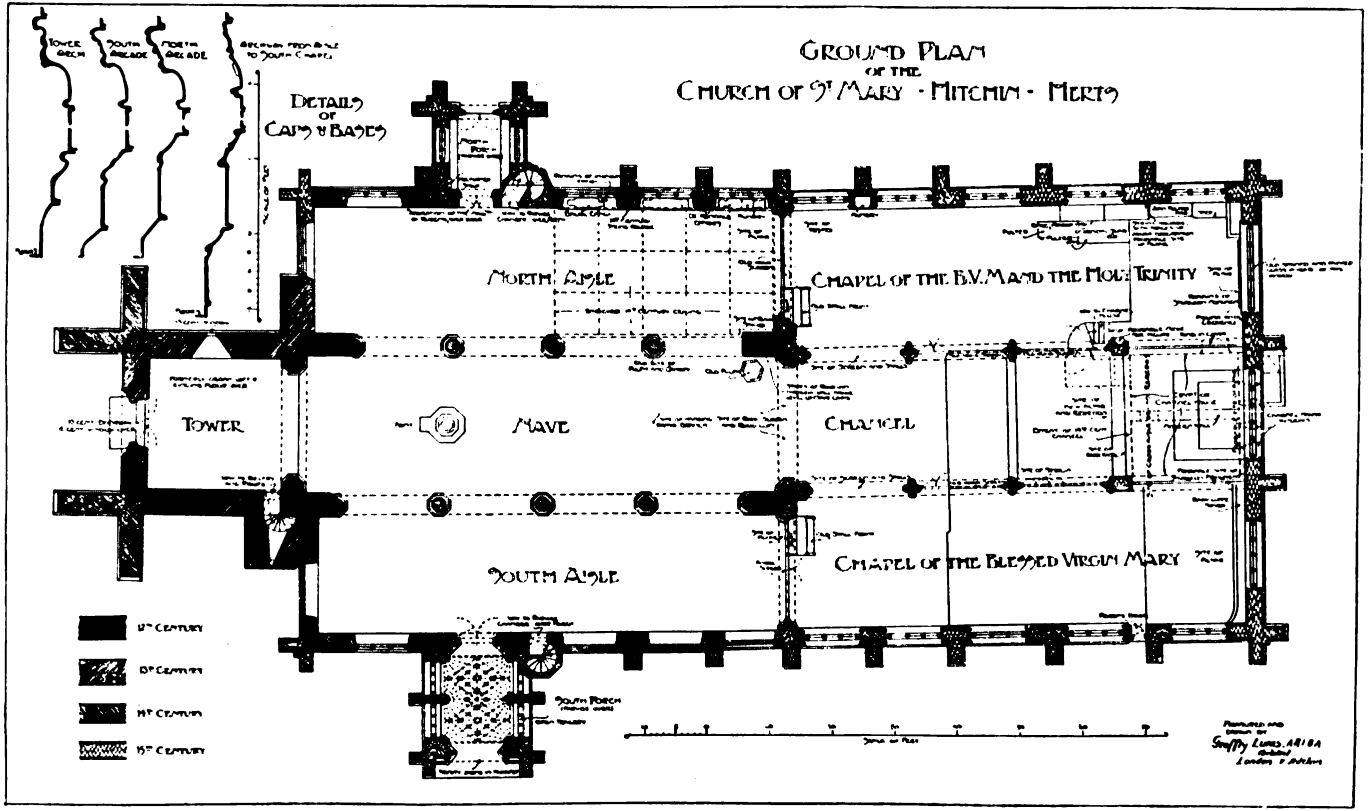
About that time, Hitchin was noted for its malt and wool trade. It would seem also to have had many vineyards, for Queen Elizabeth is said to have told a Spanish nobleman that she considered the grapes of Hitchin superior to those of his or any other country. To-day it is perhaps more popularly known for its product of lavender than for anything else. There are in England about two hundred acres of lavender fields, found chiefly at Hitchin and near Mitcham in Surrey. It has been cultivated at Hitchin since the early part of the last century.

In 1807, the mail coaches from London to Leeds passed through Hitchin for the first time, and it was not until a comparatively short time ago that they were displaced by the train service of the Great Northern. The coach from Hitchin to London had been driven by members of one family for three generations. It is no wonder that when passing under one of the newly constructed railroad bridges on his last trip to town,

the driver pointed up to the arch and said, with tears in his eyes, that it was the robber of his birthright.

Hitchin is to-day a thriving town of some twelve thousand inhabitants, a quarter of which shows the increase of the last ten or twelve years. It is but little more than a half hour out of London by train, and on the way you may get a fleeting glimpse of Hatfield, some twelve miles from Hitchin. The Bedford turnpike will lead you in a nearly straight line to Bedford, fifteen miles to the northwest, and Cambridge lies about twenty miles to the northeast. The town is in Hertfordshire but close to the Bedfordshire border and is the centre of a district of delightful rolling country, ideal for bicycle riding and filled, as is all England in fact, with scores of fascinating villages, and their offerings of parish churches, of which even the smallest will show you some mark of almost every step in the progress of Gothic building.

If you approach the town of Hitchin from the railroad station, you will leave behind you quickly the factories and more modern features which group themselves near the station and following a broad tree-arched road, find yourself shortly in Bancroft Street, the main thoroughfare of the town, and a most delightful one. About a quarter of a mile long and very wide, with many fine, brick houses, dignified in their simple treatment, with white porches sparkling against the brick and ivy, this street gives an impression of prosperity, dignity, friendliness, and answers with entire satisfaction that test of "livableness" which I apply instinctively in almost every case, a test which so few towns in Latin countries can stand and so few English towns cannot, from my point of view. These prototypes of our own early mansions make my heart jump as at the sudden sight of some old friend and I am at once filled with a desire to sign a long lease for that room just over the white Ionic porch. Then I put my hand in my pocket and feel a sixpence and a ha'penny and begin to think; and with the coming of thought, all my golden dreams take wing and I realize I am, after all, merely a Baedeker tourist, and with a last look at the window over the porch and the shaded sidewalk and the little gable opposite, I


Ground Plan of the Church of St Mary · Mitcham · Herts
Details of Caps & Bases
Tower Arch
South Arcade
North Arcade
Archway from Aisle to South Chapel
Tower
Nave
North Aisle
South Aisle
South Porch
Chancel
Chapel of the B.V.M. and the Holy Trinity
Chapel of the Blessed Virgin Mary
12th Century
13th Century
14th Century
15th Century

turn away towards High Street which will lead me by a narrower way from one end of Bancroft to the Market Place.

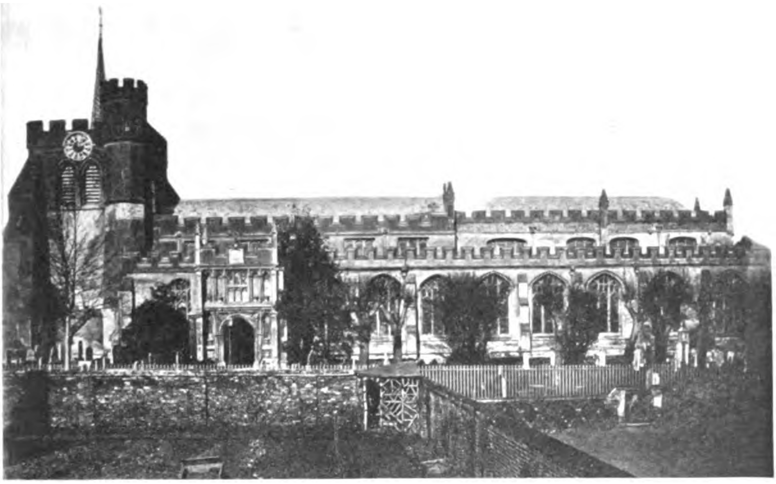
The end of High Street takes up half the width of Bancroft, the other half, now occupied by a modern store, being the site of the old Trooper Inn, whose overhanging gable once looked down the length of Bancroft Street. A narrow opening appears to the left of where the old Inn once stood, and High Street and the Market Place must wait while we explore this brick-paved winding lane which leads first between houses, then with garden walls and houses only on the right, becomes the boundary of the church-yard, giving us a first view of the Parish church of St. Mary, the low west tower of which, with its little lead covered spire, is close to our left. At the corner of the church-yard, where the lane turns down to the left, we enter a gate and get a first idea of the size of the church which stretches eastward its full width, the aisles extending along the sides of the chancel as well as the nave.

The plan which is here reproduced, made by Mr. Geoffrey Lucas, who kindly allowed me to use it, shows very clearly by the different hatchings, the growth of the structure as it stands to-day, containing work of each century from the 12th to the 15th inclusive. The church suffered much damage by hurricanes and earthquakes and by a great storm in 1362 after which the nave seems to have been entirely rebuilt, the tower alone standing intact. Perhaps this was not quite secure for large buttresses were added to it at that time. The only 12th century work remaining seems to be small pieces of wall at each end of the nave arcades. In the 15th century, the chancel and its two chapels were built, buttresses were added to the walls of the nave aisles and new windows inserted between them in the 14th century walls. The north and south porches were also built at this time.

The south porch, by which one usually enters the church, is a fine open porch entered by a wide arched opening without doors and with unglazed stone tracery in the side openings, below which are stone seats. It is vaulted in two bays with lierne vaulting. A spiral staircase opening from the south aisle leads

to a Parvise chamber over the porch. The north porch has also an upper chamber but it is much smaller, closed with doors and windows and is more simply treated than the south porch.

The outside of the church was at one time plastered but it is planned, I believe, to strip this off and let the good honest stone work face the world once more. This and other work of a like nature are fortunately in the hands of an architect who combines with a full knowledge of the work to be done a close attachment



CHURCH OF ST. MARY, HITCHIN.

for the church, and who will be sure to move with great care and tenderness in that work of restoration which is often so recklessly indulged in.

The fine old font, with its twelve much damaged apostles in canopied niches, is nearly opposite us as we enter from the south porch. It has now an imposing cover of recent construction. I believe the original cover with its simple scrolls is still in existence.

As is so often the case, the axis of the church is slightly bent where the chancel and nave are joined. The church is rich in

wooden screens, there being four interesting old ones in the chancel and two much larger ones separating the nave aisles from the chancel aisles or chapels dedicated to the Blessed Virgin Mary and the Holy Trinity. The very fine one in the south aisle is called the angel screen from its crowning feature which contains a row of angels with overlapping wings. The rood-screen has unfortunately long since disappeared. The outline of the doorway which once opened into the rood-loft can be seen close to the chancel arch and slightly above the level of the capitals of the nave piers. The little stairway leading up to it was entered from the north aisle and can easily be found though long since blocked up. A somewhat unusual feature is the low traceried window over the chancel arch.

Sir Gilbert Scott, and later Sir Arthur Blomfield, carried on considerable work in the church, freeing it of three galleries and renewing the east window and several of the roofs.

As will be seen on the plan, the 14th Century chancel was shorter by one bay than at present, having a cross aisle behind the Reredos, from the north end of which led a small stairway down to the Crypt or Charnel House.

There are a number of interesting effigies on the window sills of the north aisle and several slabs in the north chancel aisle where there is also a bit of string course bearing traces of color decoration.

In the tower are eight bells hung in 1762. On the first and second was inscribed the following amusing couplet, —

"At proper times my voice I'll raise
And sound to my subscriber's praise."

In 1901, the first was recast with a new and rather more devout inscription as follows, —

"With larger bells my voice I raise
To sound the great Creator's praise."

The eighth which seems to have been recast in 1784 says by its inscription, —

"I to church the living call
And to the grave do summon all."

On a tablet, fixed until recently in the ringer's loft, it is noted that "on Wednesday, February 20, 1782, was rung a compleat Peal of 5040 plain bob Triples in 3 hours and 28 minutes, by the ringers of this town," and then follow the names of the eight noble ringers.

The photograph of the exterior, which is reproduced, was taken years ago before some restoration was effected by Sir A. Blomfield. The clerestory windows of the chancel seen in the picture were remodelled by him and the small pinnacle between the middle two was removed.

Through an opening opposite the church-yard gate we come quickly to the wide Market Place, which is now clear but which on market days is filled with tent-covered booths, parted in two by a wide path running diagonally across the square from High Street to Sun Street. In the middle of the opposite side, is the little Renaissance building of the Corn Exchange, which, with its Palladian window and huge cupola, seems to look patronizingly at its less pretentious neighbors as if its head were slightly swelled by its possession of "a motive."

Sun Street and Bucklersbury lead away to the left from the Market Place towards Bridge Street which has many interesting gables and bits of brick-work. The town is full of these and I long for another chance to get better acquainted with them, for I spent so much time wheeling through the neighboring villages that many corners of Hitchin itself were hardly more than glanced at.

That first afternoon after a brief visit to the church and the Market Place, after a friendly handclasp, as it were, with the town, we rode to little Ickleford, which lies on the right of the Bedford Road, about two miles to the north of Hitchin. Here the church yard borders the village green where three roads meet and cross, leaving wide irregular grass plots over which one can look as he drinks his glass of "Bitter" at the sign of The Green Man.

Opposite the church, across the road by which we arrived, is the delightful group of stables and out-buildings of the Ickleford Manor through which we rode on our way home.

This short spin was a foretaste of what was to come, for the next morning we started to explore the country to the south of Hitchin, and our cyclometers had registered twenty-two miles and the evening clocks struck nine before we returned.

Starting back towards London we passed under the railroad and crossing the little River Hiz near "Nine Springs," where remains of the Roman Villa were recently unearthed, we came soon by charming roads to the village of Great Wymondley. On some of its plastered walls I saw for the first time the scratched patterns which were often seen afterwards. The patterns are drawn on the moist plaster surface with a wooden comb, the spacing of its teeth giving character to the many interesting patterns, which are formed by various swingings and pivotings of the comb.

The church of Great Wymondley dates for the most part from early in the 12th Century. It consists merely of chancel, nave and west tower. The tower was built in the 15th Century when windows were inserted in the Norman walls of the nave and chancel, which are built of small rounded stones often laid in herring-bone pattern. The chancel has an apsidal termination with three small round arched windows at the sides and a 15th Century window inserted at the east end. The old Norman chancel arch is one of the few existing in this section of the country. The south door and heavy octagonal font just inside it are also of the early period. The charmingly simple old south porch, becoming decrepit, was torn down some years ago and with that utterly false idea of "Restoration" was replaced by a new one of different design.

The simple dignity and religious spirit of this church is such as one finds only in the smaller country parishes. Here are no nave arcades to give distracting vistas. This is not the shrine to which some almost "total abstainer" makes her one yearly pilgrimage for the purpose of displaying her Easter finery. Here is only the spirit of devotion, pure and simple. The effect is that which is obtained only by the expression of some great principle in its simplest terms.

From Great Wymondley, we struck back for the main road

to the south, which we rejoined at Little Wymondley, where there are some early pointed arches and small fragments which once formed part of a cloistered Priory of Black Canons. The parish church, which was almost entirely rebuilt in 1875, is of the Perpendicular Period and from discoveries made during the rebuilding, is at least the third which has stood on that spot.

We needed no watch to tell us that lunch hour was

INTERIOR OF GREAT WYMONDLEY CHURCH.

approaching and we pushed on to Stevenage, two miles or so down the main road, where we had a bite and a bit of rest before further explorations.

The Stevenage of to-day is a town of some four thousand people and extends for the most part along either side of the main highway which is the main coach road from London to the north. The parish church of St. Nicholas is about half a

mile from the main road and marks the location of the original town of Stevenage, which was nearly wiped out of existence by a great fire in 1807, when forty-two houses were destroyed. The town rebuilt itself quite naturally along the coach road and the traffic of the rival coach lines gave good living to many inns, the gentry, travelling north from London, making this their first resting place. Besides the coaches, there were heavy wagons carrying passengers and freight. They had wheels nine inches wide to prevent their sinking into the mud and usually were drawn by six horses but in bad weather they used even as many as twelve.

The church of St. Nicholas, outside of the village, is of the later periods of Gothic building and consists of nave with aisles, chancel with chapels, and a south transept. There is also a west tower with a lead covered spire. Unlike the smaller one of St. Mary's at Hitchin, this spire is of considerable size, its base being nearly the size of the tower itself. Both these spires are covered with sheets of lead with curled joints, the edges being locked together much as one might lock his hands together by laying the fingers of one hand, palm down, on the fingers of the other hand, palm up, and then closing the fists. A heavy roll is formed at the angle and the sheets are laid at an angle with the horizontal. The smaller faces of the spire at Hitchin are covered by single rows of sheets but in the larger ones at Stevenage, the two rows overlap each other in a herring bone pattern. The church is of no mean size and suggests the well-to-do congregation of a thriving country town.

Thus far my memory of our route on that charming ride is very clear and consecutive, but here, there comes a change; for I was led from the broad highway by innumerable turnings, all quite delightful, of that I am sure, but quite confusing to my unaccustomed eye. I remember distinctly only the two churches of St. Paul's Walden and King's Walden, which marked our erratic circuit back to Hitchin. Their names are due to the fact that in these neighborhoods were deer-parks held respectively by the Dean and Chapter of St. Paul's in London and by the Crown.

The church at St. Paul's Walden consists of west tower, nave, and chancel with a south aisle and a chapel to the south of the chancel. It sits rather austerely in a somewhat unkempt church yard. Its special interest lies in the Renaissance chancel screen and Reredos of odd design which I believe are ascribed to Sir Christopher Wren. Whether this is his work or not, I do not know, but his connection with this little Hertfordshire church was evidently quite possible.

The little church of King's Walden contains work of several centuries. The nave piers with interesting carved caps are of the 12th century and the tower, while remodelled probably in the 14th century, contains work of a much earlier period. The nave has both north and south aisles and owing to the natural slope of the land, the north aisle was originally some two feet above the nave, though it is now on a level with it. The door from the north porch gives the mark of the original level. The church has fortunately saved its chancel screen, which is a good example of 14th century work. The tower is thickly covered with ivy at the bottom and with the white stones of the graveyard to the north and some fine old trees to the south and east, there is a great charm about this little church.

A slow ride home in the cool of the evening finished a most interesting day.

We made a trip to Ashwell, some nine miles northeast of Hitchin, where there is a fine church with a dignified though much weather-beaten tower, on the inside wall of which is a scratched drawing of the church, with records of the great storm of 1362 which damaged so many of the churches in this district.

It had been raining heavily all day and cleared just before sundown, leaving everything sparkling and fragrant, and the memory of our ride back, about dusk, with the perfumes of wild flowers and grasses blowing cool and delicious across the darkening meadows, will always stir in me a longing for a return to my little Hertfordshire garden of Eden.

SOME ARCHITECTURAL ELEMENTS.

The Tuscan Order.

WALTER DANA SWAN.

Instructor in Architecture

AN eminent critic has said with regard to architectural skill that trained observation, knowledge of principles, and sound judgment as to the proprieties of constructional design were most essential. It is to be noted that observation is first specified. This seems to be its natural place in our early architectural studies.

It is true that most of us fail to notice accurately the things about us until we draw them, and if while we are learning to use the instruments and conventions of our future profession, we are also learning the forms which are to become part of our vocabulary so to speak, we are serving ourselves doubly. If we have been introduced to them in the right way, our curiosity, if not our enthusiasm is aroused. We have discovered for instance for ourselves certain principles of design such as mass, scale, proportion and the values of light and shade in what was to us previously, an uninteresting column.

The master to whom we are really indebted for much of our theoretical knowledge of classical forms has been thought to have been wanting somewhat in the faculty of observation. Or perhaps his early translators did not do justice to that power of his.

This master was Vitruvius, a Roman architect of the time of Augustus who stated with great evident precision what he knew and had read of ancient architecture, and what he saw of contemporary building and its art, to say nothing of many mechanical contrivances.

At the time of the late Renaissance, with its classical interests, a Roman of the Empire was of course an authority on any matter of the arts and letters, and the formalists of the late 16th century based their theories and propped up their failing con-

structive imaginations on such a voice of authority as to each dimension for every form. These also left rules of their own.

As the student of the present day proceeds with his study of derived and natural forms he sees that questions of material, local conditions, scale and other such matters should always govern each case of the use of a form. He thus begins to see in his own experience that fixed proportions are not consistent with design and all that word means.

The elements of architecture, as treated by most of those who have followed Vitruvius, consist, as may be imagined, of the discussion of such features as walls, openings (doors and windows) porticos (the orders), arcades, roofs (vaults, cupolas and ceilings), and staircases. These are then disposed as they should be in buildings for different purposes, together with much theory and with some space given to the question of materials, and sometimes more to the dedication to some royal patron. One Englishman of the 17th century gives the following headings: "Materials, Foundation, Walls, the Appertions or Overtures, the Compartition and the Cover," and much diverting nonsense besides, as for instance, with regard to the "Foundation which requireth the exactest care; For if that happen to dance, it will marre all the mirth in the House." There were many Englishmen, Germans and Frenchmen who treated the matter in a less humorous manner than the jolly Sir Henry Wotton, and during the last century very helpful treatises on the elements, not only of the art of building, but of Design, have been written by such men as Durand and Reynaud in the earlier days of the century, and more recently by Cloquet and Guadet in France, and Bühlmann and Durm in Germany.

In beginning the observation of form in connection with conventions of architectural drawing, more or less of pure theory is necessary. In other words we have to avail ourselves of the pith of the experience of others. For instance in drawing the small building as in plate 1 we are obliged to observe carefully the different parts and we find meaning and organic character in every part. We learn here the triple organic division of almost all architectural forms and masses, the base or stereobate which

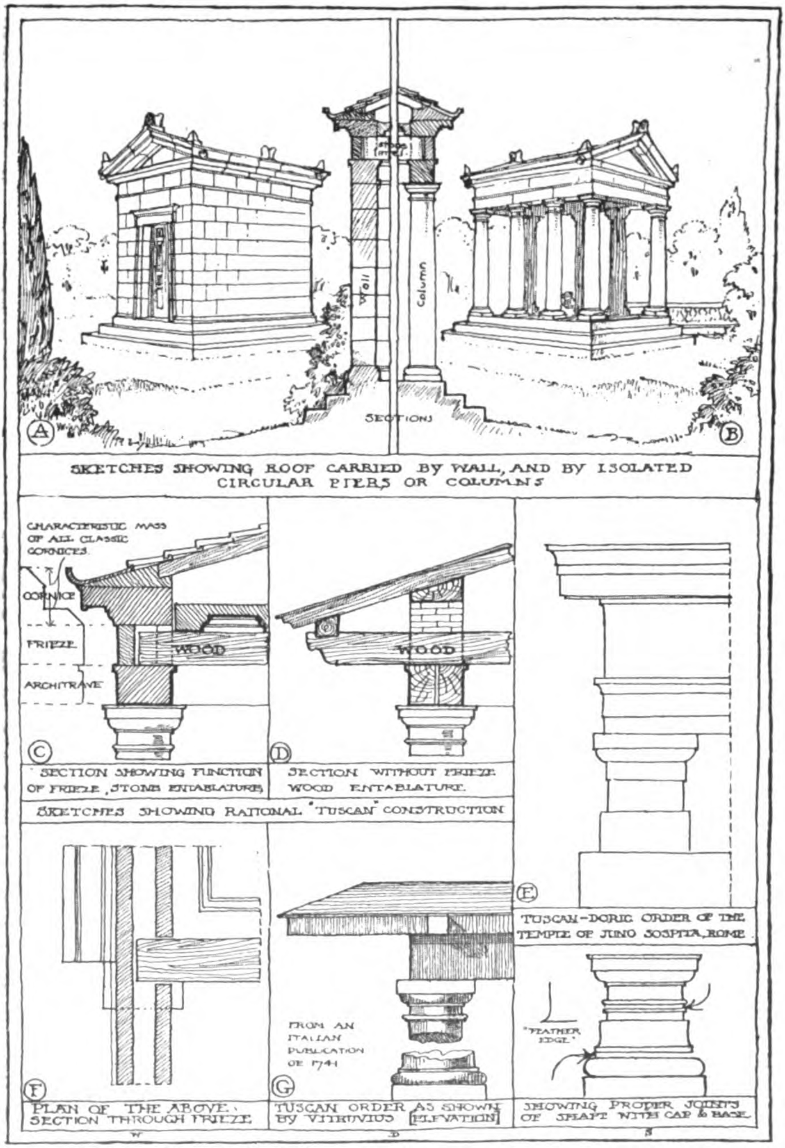

Wall
Column
SECTIONS
A
B
SKETCHES SHOWING ROOF CARRIED BY WALL, AND BY ISOLATED CIRCULAR PIERS OR COLUMNS
CHARACTERISTIC MASS OF ALL CLASSIC CORNICES.
CORNICE
FRIEZE
ARCHITRAVE
WOOD
WOOD
C
D
SECTION SHOWING FUNCTION OF FRIEZE, STONE ENTABLATURE
SECTION WITHOUT FRIEZE WOOD ENTABLATURE
SKETCHES SHOWING RATIONAL "TUSCAN" CONSTRUCTION
E
TUSCAN-DORIC ORDER OF THE TEMPLE OF JUNO SOSPITA, ROME
"FEATHER EDGE."
FROM AN ITALIAN PUBLICATION OF 1741
F
G
PLAN OF THE ABOVE. SECTION THROUGH FRIEZE
TUSCAN ORDER AS SHOWN BY VITRUVIUS [ELEVATION]
SHOWING PROPER JOINTS OF SHAFT WITH CAP & BASE

Plate 1.

connects the building with the ground, the wall itself and the protecting block or corona which covers the wall, having gutter moulding above and its supporting moulding below (another triple division) forming thus the cornice. We learn to look for this general form whenever a wall is to be crowned. Then if we substitute piers, or separate supports, for this wall we have the new element of the lintel, which has to carry the ceiling beams and the remainder of wall to support the roof, and the position of these beams would be marked on the exterior by the wide frieze of masonry, or masonry covered with stone veneer, so to speak. This bit of masonry wall carries the cornice and so we have in its logically derived form, the entablature consisting of architrave or lintel, frieze and cornice.

There has been and is much criticism of the study of the orders at the beginning of an architectural education in the light of the vast store of other material which now constitutes the elements of the art of building. Some of this criticism is due to the reaction from the formalistic period when the orders were not considered as object lessons on the principles of design, but rather more as patterns or ornaments for the decoration of buildings which were not considered as architecture without them.

Sir Henry Wotton writes as early as 1650, "I need now say no more concerning Columnes and their Adjuncts, about which Architects make such a noyse in their Books, as if the very terms of Architraves, and Frizes, and Cornices, and the like, were enough to graduate a Master of this Art."

More of this feeling of opposition is due undoubtedly to an ardent desire for the study and development of newer types better expressing the changed conditions of life and art. That other studies of the principles of design and construction should go hand in hand with the careful study of the orders is unquestioned.

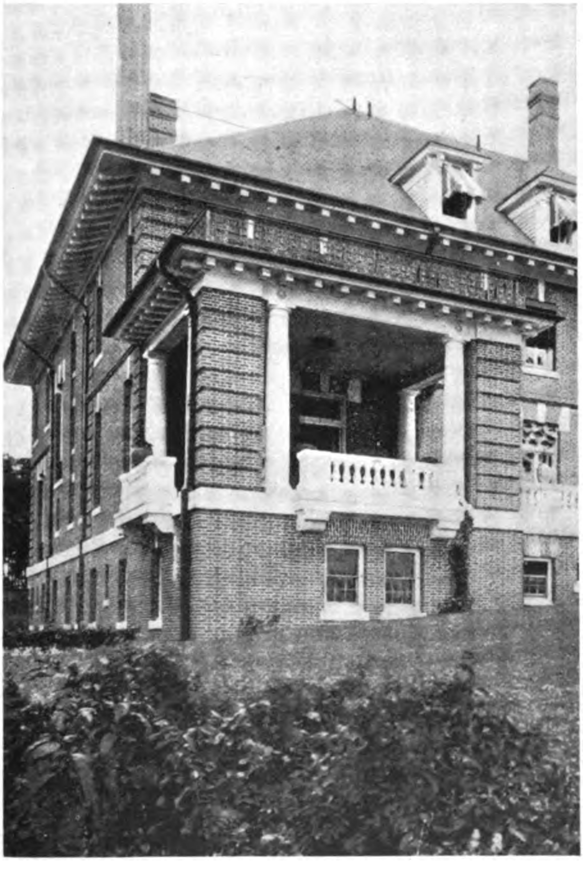
M. Guadet in his "Elements et Theorie de L'Architecture" recently published, a work in which he considers all the elements in an extremely logical manner from the point of view of the constructionist as well as the theorist, pays the following digni-

fied yet enthusiastic tribute: "The study of the orders has been moreover . . . . the pivot of modern architecture since the 16th century. In the study of walls, cornices, doors, windows, exteriors and interiors you will have to refer to it incessantly. The subject is then of capital importance and you cannot penetrate too deeply the principles." And again, "Here then is the order, that element so complete, so unqualifiedly fine, with a beauty which is that of truth. Its place in one's studies is surely most important on account of the great works with which it is identified, and also historically because for centuries it has been the principal architectural element. You cannot study it too much; not perhaps because you ought ever to have to design or build a colonnade, but because in studying it you are developing yourselves." He then continues, "But this order ought to adapt itself to numerous necessities, for however simple the architecture of a civilization may be, it has singularly varied applications. Without doubt also the ancient order lent itself to a variety of very different expressions, and of these the three great families are the Doric, Ionic and Corinthian."

Of these three great families we shall consider first the Tuscan, the country cousin perhaps of the Greek Doric Order, following the suggestion of Sir Henry Wotton, who says, "First therefore, the Tuscan is a plain, massie, rurall Pillar, resembling some sturdy, well limbed Labourer, homely clad, in which kinde of comparison Vitruvius himself seemeth to take pleasure. . . . . The Tuscan is of all the rudest pillar and his Principal Character Simplicity."

The order is but the slightly conventionalized expression of the logical forms shown in plate 1. It must be recognized however that there is in this form something more than the mere constructive requirements. There is an idea made up of reverence for racial tradition and local feeling and such non materialistic things, but it is also almost essentially a piece of sound construction expressed in an artistic manner. With regard to the history of this order we have the following statement by a modern authority. "Originating in Etruria whose

people had originally come from the Pelasgic archipelago, it was communicated to the Romans who made it a simplification of the Doric which they had received directly from Greece." It is therefore most closely related to the Greek Doric Order



LOGGIA OF COUNTRY HOUSE DESIGNED BY MESSRS. CARRÈRE AND HASTINGS SHOWING "TUSCAN" CONSTRUCTION.

which we shall find to be the most completely developed form of lintel construction ever devised, but so organic in its use in the Greek temple that it seems unnatural to use it to express conditions differing from the original ones. The Tuscan Order

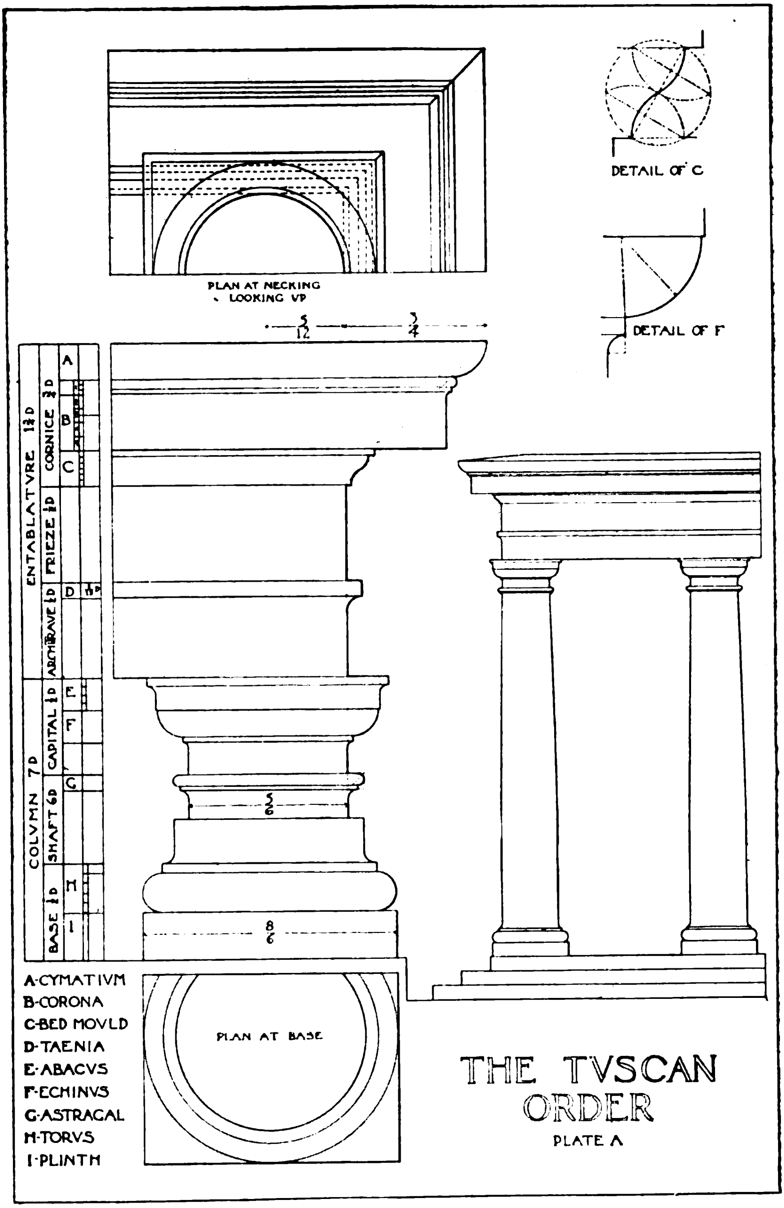
on the contrary has had a life of continous change and adaptability, and rational relation to partial wooden construction has kept it largely in active service. It has developed such use as that shown on page 51 and as in certain examples about the University here, the memorial gate of the class of 1875 and. the north porch of the Harvard Union. These two latter cases to be sure show certain properties of the form of the Doric order as used by the Romans, and also much Ionic influence, but they are good examples of the order used as a means to a desired end, and modified with freedom and intelligence.

It seems a far cry from the Etruscan temple as described by Vitruvius to such modern use as is shown in the loggia by Messrs. Carrère and Hastings, but the lack of the frieze, the ends of the ceiling beams projecting to support the overhanging and shading roof, and the wide intercolumniation proclaiming the wooden architrave, show the life in a form which we perhaps associate with musty books.

By such a historic example as that of the "Temple of Juno Sospita" is shown the mingled respect of the Romans for the Greek Doric order and their idealization of the simple Etruscan form of their more Italian ancestors. But whatever the forms of the mouldings may be the plain frieze covering the ends of the ceiling beams or trusses, if they are cut short as at C, and the omission of the frieze allowing the projection of the same beams or trusses as at D are the constructional features which seems likely to persist along with the more conventionalized wholly stone treatment as formulated by the Renaissance Master, Giacomo Barozzio, called Vignola, and shown here in our diagrams of the Tuscan order on plates A and B.*

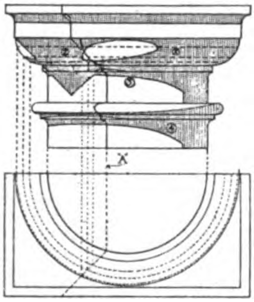
Here we see the three principal parts of the order whose characteristics we have somewhat noted. The base or stereobate, the column, and the entablature. We shall see them more fully developed and with more unity when we study the Greek Doric order, but not with such simple elements.

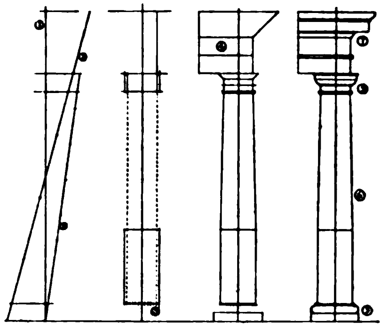
*The plates A and B were drawn by A. E. Hoyle, '04, from data furnished by the Department of Architecture, which is indebted for some features to Prof. W. R. Ware, late of Columbia University.



THE TVSCAN ORDER

PLATE A





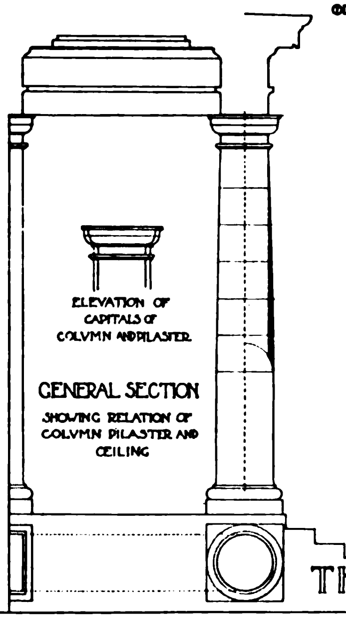
SHADE·AND·SHADOW·ON·CAPITAL:

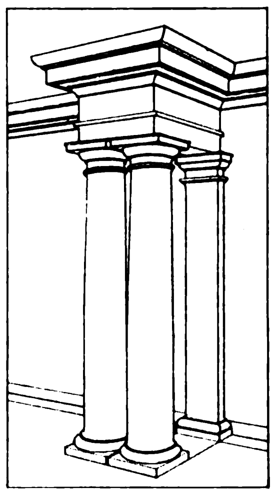
FIRST: FIND SHADE OF ECHINVS, ① SHADOW OF ABACVS ON ECHINVS ② AND SHADOW OF EDGE OF FILLET ON NECKING ③, BY MEANS OF SECTIONS LIKE "X". SECOND: FIND SHADOW OF SHADE LINE OF ECHINVS ON NECKING ④

SEE VIGNOLA (ESQVIÉ) PLS. LVIII, LIX.

METHOD·OF·DRAWING·THE·ORDER·GIVEN· AXIS·AND·TOTAL·HEIGHT·

① LOCATE AXIS OF COLVMN. ② DIVIDE HEIGHT OF ORDER INTO 5 PARTS: ENTABLATVRE = 1 PART, COLVMN = 4 PARTS; LOWER DIAMETER = 1/7 OF COLVMN. ③ FIND VPPER DIAMETER ON LOWER AND PROJECT THROVGH ENTABLATVRE. ④ DRAW TOP LINE OF ARCHITRAVE AND FRIEZE; DRAW FROM LATTER A LINE AT 45° GIVING MASS OF CORNICE. ⑤ DRAW ELEVATION OF CAP AND BASE. ⑥ CONSTRVCT ENTASIS AND DRAW SHAFT ⑦ DRAW PROFILE AND SMALLER HORIZONTAL MEMBERS





THE TVSCAN ORDER

PLATE B

The square plinth or block on which the column rests would undoubtedly have been found inconvenient by the Greeks themselves, but owing to the wide intercolumniation due to the wooden lintel or its tradition, the square base does not interfere with passers.

Theoretically the circular form of the shaft is due to the same desire for space, as the original isolated supports were first roughly square and then polygonal, as shown in Egyptian forms, and then the angles were gradually removed.

As the architrave or lintel must be square to carry wall above it the capital must effect happily the transition from round to rectangular, and how could it have been done more simply than by the firm circular echinus? The shaft itself constructively includes the fillet or flat moulding at its top and bottom, as one can see the impracticability of having a "feather edge" as shown in the sketch in Plate 1, if the shaft was of such a scale as necessitated a joint of the base mouldings with the shaft. It is a slight misfortune therefore that our useful measurements cannot conveniently correspond in this case with the form, as they have been adapted elsewhere to the simplest common terms. When the Doric order is studied the reasons for the form of the cornice will be further observed, but the separating mouldings, the drip or cutting of the under side of the corona to prevent water from running in toward the joint of the frieze and cornice, may be observed here in this elementary relative to the Greek Doric.

As for the drawing of this order in which process we really become acquainted with the form, if we use our minds as well as our fingers, these plates may be of service, showing only, it must be remembered the conventional projections of the form, and not its real aspect with its contrast of surfaces and its play of light and shade. Those qualities can best be appreciated by noticing such examples of this form as those referred to above, as here at Harvard.

The unit of measurements in these plates is the lower diameter, a simplification of the "Module" or one half diameter as used by the Renaissance masters in their formulas. It was

the custom to give dimensions in these terms for the distance between columns, a dimension which seems evident to most of us now must depend on the length of the stone obtainable for the lintel, the scale of the order and such practical considerations. The intercolumniation here shown is a reasonable one to be kept in the mind's eye without the necessity of a fixed dimension. The other features of plate A explain themselves. On plate B is shown the method of drawing the order or "blocking out," an unsatisfactory expression for the orderly indication of the importance of mass first and detail afterwards. It is a useful exercise in systematic attack of any problem of drawing and is found to be of the greatest practical service to the draughtsman when it has become second nature and is not a too conscious process, as of course it is in the early stages.

That the shaft contracts noticeably in diameter between base and capital ought to be readily observed, but that this contraction takes the form of a delicate curve might readily escape the eye. This feature is called the entasis and the principal method employed in finding it is shown.

The points on the arc of the circle are equal divisions of sixths of that portion of the arc contained between the vertical projection of upper and lower diameters of the shaft, and these sixths are projected up vertically to the horizontal lines dividing the upper two thirds of the shaft into sixths. Where these intersect are found the points through which one must draw the outline of the entasis.

The dimensions given here on these plates will serve to help in memorizing the form, but they are only expedients to that end, and should be forgotten when once the form is mastered by the memory. It is a recognized fact in the experience of all of us that we are not really and intimately familiar with a form until we can draw it from memory. Our knowledge is not definite, our imagination has no point of departure, and to have mastered a simple form like that of the Tuscan Order so that it can be drawn from a knowledge of its proportions and parts and not from the dull figures with which we at first learn it, has the pleasure not only of a conquest but of a creation.

THE INDUCTION MOTOR.

INTRODUCTION.

ONE statement of the law of electromagnetic induction is, that whenever a wire is moved sidewise across a magnetic field, an e. m. f. is induced in the wire, which is at each instant proportional to the rate at which the magnetic flux is cut by the wire, and in such a direction as to oppose the cause. Since motion is relative, the same result would be accomplished by causing the flux to cut across the wire.

In either case the resulting current will be so directed as to oppose the relative motion between wire and flux. In the latter case, the electromagnetic drag on the wire will be such as to urge it along in the same direction as that in which the field is moving, or we may say that the flux is dragging the wire after it (figure 1). Going a step farther, a closed loop of wire will tend to rotate when placed in a rotating magnetic field.

This is in principle an induction motor, and consists essentially of two parts, a rotating magnetic field and a short-circuited armature free to rotate therein.

If the rotation of the field could be obtained only by mechanical means, *e. g.*, by rotating the field magnets of a dynamo about the armature shaft, the device would have no commercial value other than as an electromagnetic coupling. The practicability of the induction motor, however, lies in the fact that the rotating field may be produced in a very simple manner, by means of polyphase alternating currents circulating in overlapping stationary * coils.

The production of a revolving m. m. f. by the combination of two or more alternating m. m. f.'s differing in time phase and set at different angles, is roughly analogous to the production of

* It is evidently possible to produce the revolving field about the periphery of a structure free to revolve, and to have the short-circuited armature stationary, in which case the field structure would revolve in a direction opposed to that in which the flux revolves around the field structure. This is not a common arrangement.

an approximately uniform turning moment at the crank shaft of a steam engine by the combination of the properly timed impulses of two or more pistons acting on cranks set at different angles.

The combination of a rotary field thus produced with a short-circuited armature, constitutes an induction motor; "induction" because the armature currents are *induced* by the movement of the field flux, whereas in most other types of the

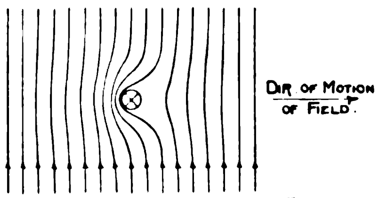
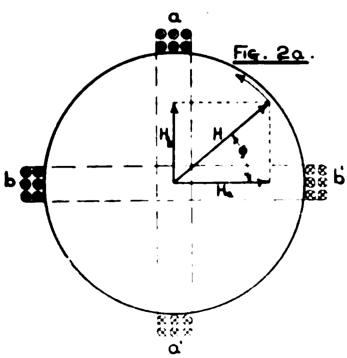
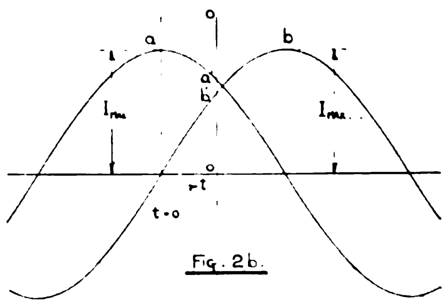


Fig. 1. Direction of Induced E.M.F. and Current Back through Paper.





electic motor the armature current or currents are *con*ducted into the armature through sliding contacts. In the latter case the field plays only a passive part and the energy to be transformed is *con*ducted into the armature electrically, while in the induction motor the energy is transferred by *in*duction to the armature, the armature currents induced by the movement of the flux reacting upon that flux to produce rotation.

What are here called the "armature" and the "field," are fre-

quently called the "rotor" and the "stator," respectively. The armature is usually the revolving part, but since the reverse is sometimes the case, the above nomenclature is sometimes misleading. Later on the field will be referred to as the "primary" and the armature as the "secondary."

THE PRODUCTION OF A ROTARY FIELD.

Consider two coils of wire with their planes at right angles (Fig. 2a), supplied with two simple harmonic currents of the same frequency and magnitude, but differing in phase by 90° (Fig. 2b). Each current will produce a magnetic force perpendicular to the plane of its coil, and of a magnitude proportional to that of the current at the instant under consideration.

Consider the instant corresponding to the line $\overline{oo}$ (Fig. 2b); then $\overline{oa'}$ will be the magnitude of the current in coil $\overline{aa'}$ and $\overline{ob'}$ that of the current in coil $\overline{bb'}$. Represent the corresponding magnetic forces at the center of the coils by H_a and H_b (Fig. 2a), and their resultant by H.

Counting time from left to right in Fig. 2b, H_a is decreasing and H_b increasing at the instant $\overline{oo}$ represented in Fig. 2a. As H_b increases to its maximum value and then decreases, H_a decreases to zero, reverses direction and increases. During this same period, H has swung around to the left, first to the vertical position and then beyond.

The magnitudes of these magnetic fields at any time $\underline{t}$ may be expressed as follows:

$$H_b = H_{max} \sin \omega t$$
$$H_a = H_{max} \sin (\omega t + 90°) = H_{max} \cos \omega t$$
$$H = \sqrt{H_a^2 + H_b^2} = H_{max}$$

which is constant in magnitude and equal to the common amplitude of the two component fields.

The angular position, ϕ, of H, at any time t, is such that $\tan \phi = H_b \div H_a = \tan \omega t$, and $\phi \div t = \omega$, which is constant.

Thus the resultant field is constant in magnitude and revolves with a uniform angular velocity, $\omega = 2\pi n$ where n is the com-

mon frequency of the two currents; *i. e.* H makes one complete revolution for each complete cycle of the current.

In a similar manner it can be easily proved that three equal simple harmonic currents of the same frequency, but differing in phase by 60°, flowing in three concentric similar coils with their planes set at sixty degrees from each other, or that m such currents differing in phase by $\frac{180^\circ}{m}$ and flowing in m coils differing in angular position by $\frac{180^\circ}{m}$, will produce a uniformly revolving field of constant magnitude.

The number of such currents is limited by the increased cost and complication due to the large number of conductors connecting generator and motor. In practice the number of currents rarely exceeds three, although in a few cases as many as six are employed.

Laminated Iron Cores. As it is desirable to reduce the reluctance of the magnetic circuit as much as possible, both the stationary structure (the field core), which supports the field coils above considered, and the revolving structure (the armature core), which carries the short-circuited armature coils, are made of iron. They are also laminated throughout, since both undergo continuous flux changes. The plane of lamination is that of rotation, perpendicular to the axis of armature rotation.

Leaving the armature for the present, consider a few of the possible arrangements of the field winding.

FIELD WINDINGS.

Fig. 3 shows a two phase field where each coil is embedded in a pair of large slots. The flux corresponds to the instant $\overline{oo}$ (Fig. 2b), and is the same in direction as that of Fig. 2a.

The presence of the large slots of Fig. 3 causes a considerable disturbance in the magnitude and uniformity of rotation of the field, to avoid which difficulty each coil or phase is usually distributed in several pairs of small slots, as in Fig. 4, where each phase is distributed in six pairs of slots, the two *belts* of conduc-

tors designated *a* and *a′* corresponding to the two sides of coil $\overline{aa'}$ of Figs. 2a and 3, and the belts *b* and *b′* to the two sides of coil $\overline{bb'}$.

In a three phase distributed winding there would be six *belts* of conductors, each occupying 60° of the inner periphery of the field, two diametrically opposite *belts* for each phase.

The disturbing effect of the slots may be still further reduced

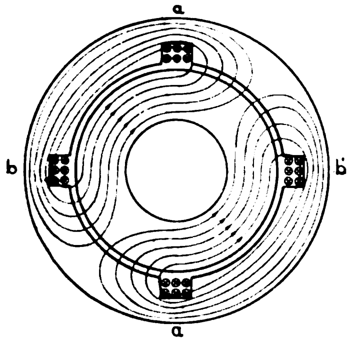


Fig. 3.

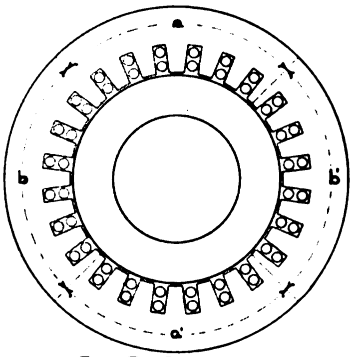


Fig. 4. Two Phase. Two Pole Distributed Field Winding. Six Slots per Pole per Phase.

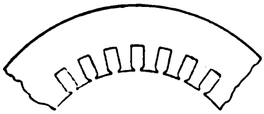


Fig. 4a.

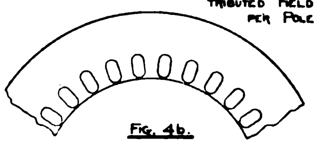


Fig. 4b.

by partly or wholly closing the slot openings (Figs. 4a and 4b).

The factors which determine the slot proportions will be considered later.

Multipolar Windings. Thus far two pole fields only have been considered, *i. e.* fields in which there is one complete coil or two * belts of conductors, per phase, in which the m. m. f. and flux make one complete revolution per cycle of current, and in which there is a single *space* † cycle of flux distribution.

* In the closed coil, three-phase winding, there is only one belt (120°) per phase. This is rarely if ever used for induction motors and will be described at another time.

† There are two distinct variations of the flux density in the air gap of an induction motor; the variation from time to time at any fixed point as the flux revolves, and the variation from point to point around the gap periphery at any given instant. The former is called the time variation and the latter the space variation or space distribution. A space cycle thus comprises a complete cycle of space flux variation.

It is usually desirable, however, to have a much lower speed of field revolution than that given by a two pole winding supplied with currents of ordinary frequency. *E. g.* 60 cycles per second would correspond to 3600 r. p. m. of a two pole field, irrespective of the size of the machine. In order to reduce this speed it is necessary to employ multipolar field windings.

A two-phase four-pole field is shown in Fig. 5, the flux cor-

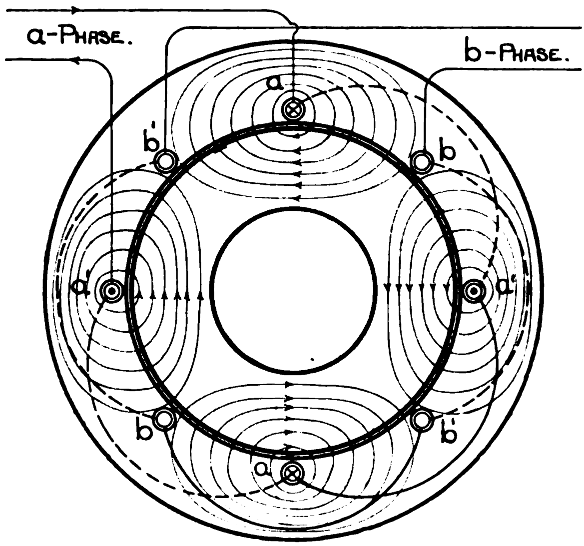


Fig. 5. Two Phase. Four Poles One Slot per Pole per Ph.

responding to the instant when the *a* current has its maximum value and the *b* current is zero. For the sake of simplicity the winding is shown with one slot per belt and one conductor per slot.

A little consideration will show that in this case two complete current cycles are required for a complete revolution of the magnetic field, and that there are two complete space cycles of flux distribution, or four poles, at any instant.

Similarly with a six pole winding, there will be six conductor belts per phase, three space cycles of flux, and three current cycles per revolution of the field.

In any case there is one conductor belt per pole per phase, and the number of slots in each belt (the number of slots per pole per phase), is a measure of the degree of distribution of the winding. This number varies from two to eight, depending upon the frequency, the peripheral velocity, and the size of the machine.

From the foregoing it is clear that the following requirements in connection with the field winding are vital: all the conductors in any one belt must be connected in the same direction,

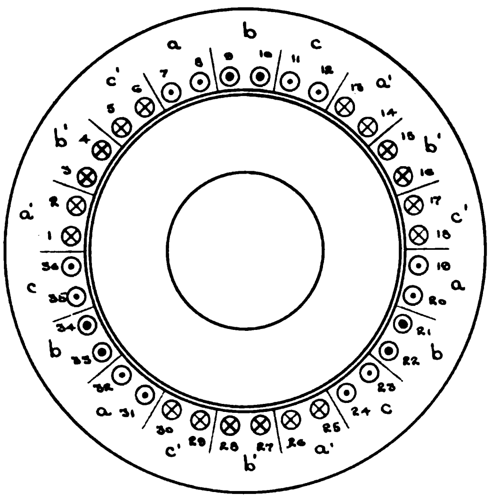


FIG. 6. SIX POLES. THREE PHASES.
TWO SLOTS PER POLE PER PHASE.

i. e. so connected that the current must flow in the same direction in all of them at the same instant; adjacent belts in the same phase must be connected in opposite directions, or alternate belts in the same phase must be connected in the same direction.

A six-pole, three-phase field, with two slots per pole per phase, is illustrated in Fig. 6. The a and a' belts belong to one phase the b and b' belts to another, and the c and c' belts to the third. All the a belts are connected in one direction and all

the a' belts in the opposite direction; similarly with the other phases.

The dots and crosses in the slots designate primarily the relative direction of connection of the several belts of each phase, but in this case also designate the relative direction of the currents in the several phases at the instant when the current in the b phase has its maximum value.

End Connections.

As yet nothing has been said of the end connections between the several active or slot conductors of each phase, but the manner of making these does not affect the m. m. f. and flux across the air gap, as long as the above conditions with regard to the relative direction of connection of the slot conductors are satisfied.

There are several methods of making the end connections, among which are the following, which refer to Fig. 6. Each method is illustrated by a winding table, in which the order of the figures indicates the order of connection of the active conductors, and in which the plus and minus signs indicate the relative direction of progression across the gap periphery, in following the winding of each phase from one end to the other. The a phase is chosen in each case.

Double Coil Winding. $+ 2 - 7 + 13 - 8 + 14 - 19 + 25 - 20 + 26 - 31 + 1 - 32$. Each slot is here represented as carrying a single conductor, but ordinarily each slot contains several conductors, in which case the conductors of two similar slots of the same phase are wound into a coil. *E. g.*, in the present case, the conductors in slots $\underline{2}$ and 7 would be wound into a coil, one end of which would be a terminal of the a phase and the other connected to the coil in slots $\underline{13}$ and $\underline{8}$, as indicated in the winding table. The remaining coils in the a phase are, $14 - 19$, $25 - 20$, $26 - 31$, and $1 - 32$.

This is called a double coil winding because there are two coils per pair of poles per phase.

Single Coil Winding. $2 - 7 + 1 - 8 + 14 - 19 + 13 - 20 + 26 - 31 + 25 - 32$. In this case the conductors in slots $\underline{1}$, $\underline{2}$, $\underline{7}$ and $\underline{8}$ are wound into a single coil in the manner indi-

cated in the table, similarly with the other conductors of the *a* phase. There is thus only one coil per pair of poles per phase.

The advantage of this over the double coil winding is that there are fewer crossings between the end connections of the several phases, which is an advantage chiefly in machines of relatively high voltage.

The mean length of one turn of wire is evidently greater in this case than in that of the double coil winding.

Wave winding. 1 − 7 + 13 − 19 + 25 − 31 + 2 − 8 + 14 − 20 + 26 − 32.

Lap winding. 1 − 7 + 2 − 8 + 13 − 19 + 14 − 20 + 25 − 31 + 26 − 32.

In either of these windings the conductors in coils 1 and 7 would make up one coil, 2 and 8 another, 13 and 19 another, and so on. The only difference between the two is in the order of connecting up the several coils

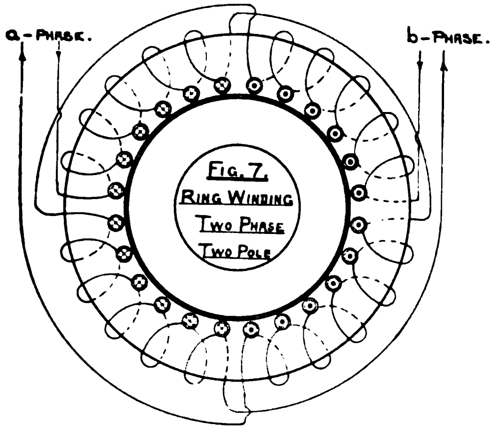
These two methods are particularly adapted to the use of form-wound coils, since each coil has the same shape as every other. The completed winding looks just like that of a closed coil d. c. machine, and the coils are laid in the slots in the same order.

The mean length of one turn is about the same as that of the single coil winding, but the number of crossings at the coil ends is greater than in either of the other cases. These methods are therefore best adapted to moderately low voltage machines.

Ring winding. This method is illustrated in Fig. 7, which shows a two-phase, two-pole field with six slots per pole per phase. Each phase belt is wound into a single coil by carrying the end connections around the field ring, and the adjacent belts of each phase connected in opposite directions. The result is obviously the exact equivalent of the drum winding so far as the active conductors are concerned, the only difference being in the disposition of the end connections.

Since there are the same number of conductors on the outer as on the inner periphery of the field core, and arranged in the same relative order, there will be a revolving m. m. f. outside as well as inside.

This method would, for a multipolar machine, give a much greater length of idle wire than any of the drum windings, but a reduced length in the case of a bipolar machine of ordinary proportions. It also occupies much less space parallel to the shaft.



Closed coil winding. This may be either drum or ring, but the latter will be used for illustration, the principle being the same in both.

Fig. 8 shows a closed coil, two-pole, ring winding, tapped at three points, 120° apart. If three equal alternating currents of the same frequency, but differing in phase by 120°, be supplied to this winding at the three tapping points, they will divide symmetrically in the winding so that the three belts will carry three equal currents, 120° apart. The result will be a revolving m. m. f. around both the inner and outer periphery of the core. In the case of the closed coil drum winding placed in slots on the inner periphery of the core, there would be no m. m. f. on the outside.

In either case the active conductors are divided into three equal belts, and the winding is best classified as a *three-belt* winding, since the ordinary three-phase winding is a *six-belt* winding. In the former case each current crosses the face of the core in only one direction, while in the latter each current crosses the

face of the core in two places, in opposite directions, Fig. 7, thus supplying two current belts, in which the currents are 180° apart. In the former case each belt is broad, and during much of the time the current in some of its conductors is opposing the flux generated by the current in the remainder, while in the latter case each belt is narrower and the currents in its several conductors act more in unison. This reduces very considerably the effectiveness of the three-belt distributed winding.

If a two-pole, closed coil winding, with four equidistant tap-

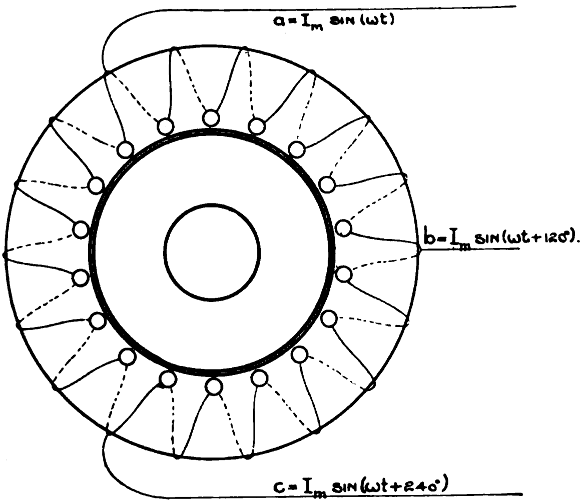


FIG. 8. TWO POLE, THREE PHASE, CLOSED COIL, RING WINDING.

ping points, be supplied with four, equal, alternating currents 90° apart, the result will be identical to that obtained by the ordinary two-phase four-belt winding of Fig. 7. Six equidistant tapping points supplied with six alternating currents 60° apart will give the same result as that obtained by the ordinary three-phase six-belt winding. In either of these last mentioned cases, there are six equal belts, in which the currents differ in phase progressively by 60°.

The above refers strictly to two-pole winding only, but the

change to multipolar is an easy step. *E. g.*, in the three-phase, *four-pole*, closed-coil winding, there are six equidistant tapping points, and six equal belts; each two diametrically opposite tapping points are connected together, and the three pairs are the three terminals. In this way, each two diametrically opposite belts are connected in parallel instead of in series as in the ordinary four-pole winding. In the six-pole machine there are three similar belts connected in parallel for each phase and so on.

The greater the number of belts per pair of poles, the narrower will be each belt, the more will its current act as a unit, and the smoother will be the rotation of the field.

The closed coil winding is never used in a machine intended primarily as an induction motor, but the induction motor action of such windings is frequently made use of in starting synchronous converters, where this type of winding is necessary.

Pole winding. Another type of winding rarely employed is the pole winding shown in Fig. 9. This is a two-phase, two-pole field, for although there are four mechanical poles, there are at any instant only two resultant magnetic poles.

The flux is shown corresponding to the instant when the two currents *a* and *b* are equal and in the same direction (fig. 2a). Forty-five degrees later in the current circle, *b* will have its maximum value, *a* will be zero, and the resultant flux will be from pole 2 to pole 4; 45° later the flux will be diagonally from poles 2 and 3 to poles 1 and 4, and so on, making one complete revolution for each current cycle.

The disturbing effect of the large poles and intervening spaces is very great, but there is another very serious objection to this type, namely, that the cross-section of the magnetic circuit linked with any one coil is very small as compared with that of the corresponding drum winding (Fig. 3), and the reluctance correspondingly large. The effectiveness of the current is thus greatly restricted.

This type of field winding is never employed where the machine is to be used primarily as an *induction* motor.

M. M. F. AND FLUX DISTRIBUTION IN THE AIR GAP.

The first consideration of the rotating magnetic field was made (page 59), by determining the resultant magnetic force at the centre of a system of coils, and by assuming the flux proportional to the magnetic force; but in the kind of magnetic circuit now under consideration, including iron path and air space, and with distributed windings, it is necessary to consider more carefully the nature of the rotation of the field and its distribution along the air gap at any instant. This last is especially

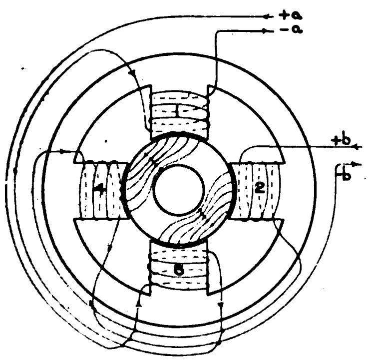
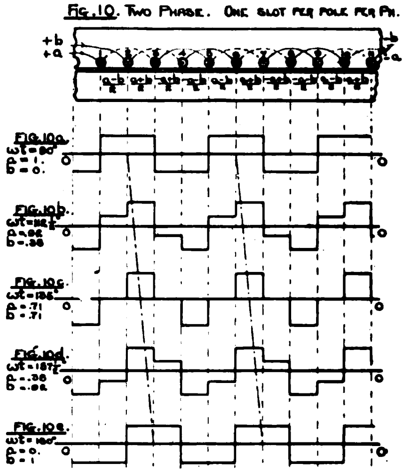


Fig. 9. Pole Winding.

Fig. 10. Two Phase. One slot per pole per Ph.



important since it is upon this that the induced e. m. f. in the armature coils depends.

The consideration of the flux distribution in the air gap is somewhat simplified by the fact that the densities commonly employed in the field and armature cores are comparatively low, in order to avoid excessive core losses.* The result of this is, that of the m. m. f. around any elementary magnetic circuit which crosses the gap twice and links with certain field currents, much the larger part is consumed in the gap, only a small part being required for the iron.

* There is not the same necessity for low density in the armature core as in the field, since the former is revolving with the flux, and the frequency of reversal is much reduced.

Therefore, to find the ampere turns consumed in the gap at any point, it is only necessary to follow the circuit of the flux at that point and to divide by two the ampere-turns linked with that circuit.

Consider first a two-phase field with one slot per pole per phase. Imagine the field and armature cores cut radially and straightened out, and consider an edgewise view (Fig. 10). Designate the two currents by $\underline{a}$ and $\underline{b}$, then since they are assumed to have the same maximum value;

$$\left.\begin{aligned} a &= I_{max} \sin \omega t \\ b &= I_{max} \sin (\omega t + 90^\circ) = I_{max} \cos \omega t \end{aligned}\right\} \quad . \qquad (1)$$

For convenience take $I_{max} = 1$, then; $a = \sin \omega t$ and $b = \cos \omega t$. Assume one conductor per slot and take $\underline{a}$ and $\underline{b}$ as positive when progressing through the winding from left to right in the figure, as indicated by the arrow heads. Count the flux across the gap as positive when directed downwards in the figure, from field to armature.

Consider an instant when $\underline{a}$ and $\underline{b}$ are both positive in the sense above described; then the m. m. f. between the slots 1 and 3 will be downwards across the gap as far as the current $\underline{a}$ is concerned; between 2 and 4 downwards due to current $\underline{b}$; between 3 and 5 upwards due to $\underline{a}$; between 4 and 6 upwards due to $\underline{b}$; and so on. Adding these overlapping m.m.f.'s together and expressing their sum in terms of ampere turns, gives: between 2 and 3, m. m. f. across gap is $\frac{a + b}{2}$; between 3 and 4, $\frac{-a + b}{2}$; and so on, as indicated on the figure.

Starting with the instant when $\omega t = 0$, Equation (1), the corresponding m. m. f. distribution along the gap is shown in Fig. 10a. Figs. 10b, 10c, 10d, and 10e show in a similar manner the m. m. f. distribution at successive intervals, indicated on the figures.

The diagonal lines indicate the progression of the m.m.f. Owing to the natural dispersion of the flux, it will undergo no such abrupt changes in density as appear in the m.m.f.

curves; otherwise the curves showing the flux distribution in the gap would have the same general shape as those of m.m.f.

An inspection of these curves shows that although the flux as a whole is progressing along the gap to the right, the nature of its space distribution varies considerably from one instant to another.

It is obvious that the steps in these curves may be increased in number and decreased in magnitude by increasing either the number of phases, or the number of slots per pole per phase, or both.

Figs. 11, 11a, etc., show the results of the same kind of analysis for a three-phase field with four slots per pole per phase. The currents will be called positive when in the directions indicated by the arrows on the end connections and by the dots and crosses on the active conductors in Fig. 11.

The three currents are —

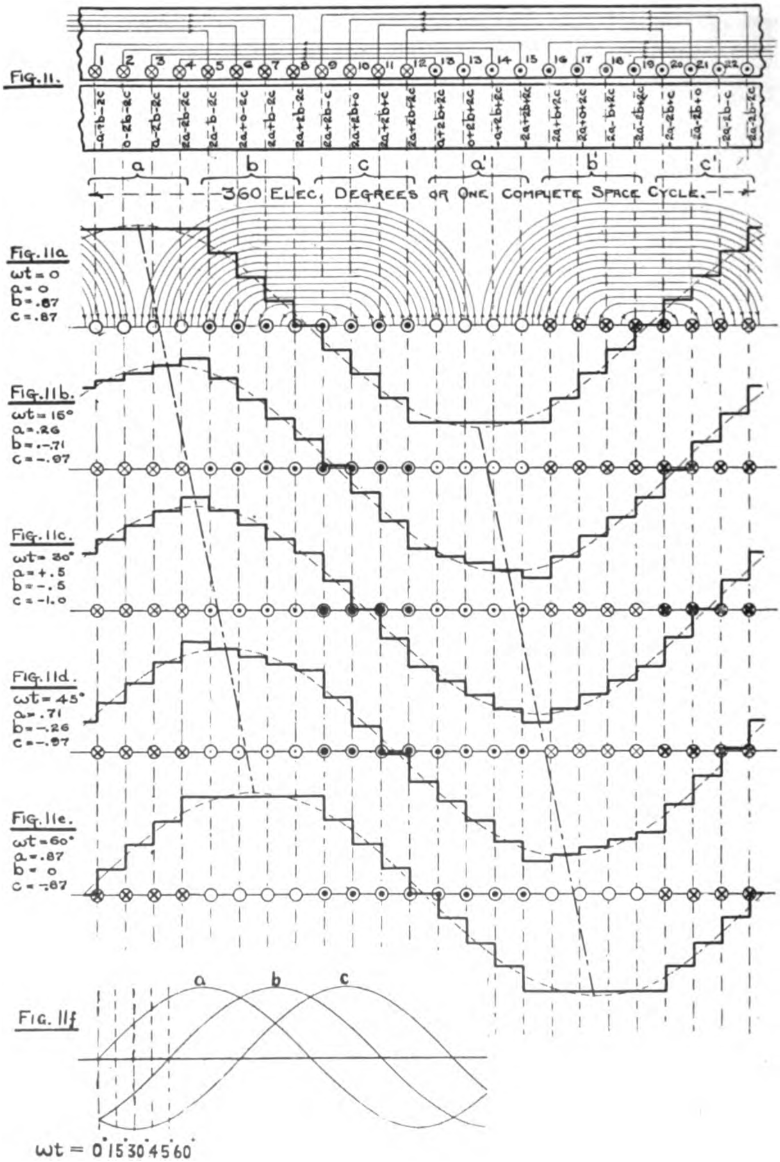
$$\left.\begin{aligned} a &= I_{max} \sin \omega t \\ b &= I_{max} \sin (\omega t - 60^\circ) \\ c &= I_{max} \sin (\omega t - 120^\circ) \end{aligned}\right\} \quad . \quad . \quad . \quad . \quad (2)$$

These are plotted in Fig. 11f. Take $I_{max} = 1$, then, $a = \sin \omega t$, $b = \sin (\omega t - 60^\circ)$ and $c = \sin (\omega t - 120^\circ)$.

The relative directions and, roughly, the magnitudes of the currents in the several belts are shown for each curve by the dots and crosses along its axis.

Counting the m. m. f. and flux as positive when downwards across the gap, and expressing the m. m. f. in terms of the ampere turns, as in the preceding example, we have: the m.m.f. across the gap, due to the a current, is $2a$ between slots 4 and 13; $-2a$ between 16 and 25; a between 3 and 4, and between 13 and 14; zero between 2 and 3, and between 14 and 15; $-a$ between 1 and 2, and between 15 and 16. Similarly with the other phases. Adding together the overlapping m.m.f.'s of the three phases gives the totals indicated in Fig. 11.

Starting with $\omega t = 0$, we have $a = 0$, $b = -.866$, and $c = -.866$. Substituting these values and plotting, gives Fig. 11a; Figures 11b, 11c 11d and 11e were obtained in a similar



The stator slot numbers in Fig. 11 are misplaced from no. 13 on. The numbers in text refer to the correct slot numbers.

manner for the successive intervals indicated thereon. The dotted curves are equal sine curves, each having an area equal to the average area of the actual m. m. f. distribution curves. The diagonal lines indicate the progression of the flux as in Figs. 10a, 10b, etc.

In Fig. 11a there is also shown the approximate path of the flux on one side of the air gap, the direction of the flux being indicated by the arrow-heads. The axis of the curve is taken as the line of the developed air gap.

Angular Velocity of Field Rotation. Since the portion of the gap periphery shown in Fig. 11 corresponds to one pair of poles, 360 electrical degrees, or one space cycle, the curves show that during the time occupied by one-sixth of a current cycle (from $\omega t = 0°$ to $\omega t = 60°$) the m. m. f. has progressed along the air gap a distance corresponding to one-sixth of a space cycle, or 60° (electrical). Therefore, the electrical angular velocity with which the m. m. f. and flux revolve around the air gap is $\omega = 2\pi n$, where n is the frequency of the impressed currents. Also, if p' is the number of pairs of poles, the number of mechanical revolutions of the flux per second is $n \div p'$ and r. p. m. $= 60\, n \div p'$.

Although neither the maximum ordinate nor the area of the half wave of m. m. f. distribution (which is a measure of the flux from one pole), is constant from one instant to another, the variation is very small in the case illustrated. As above explained, the curves of flux distribution will not show such abrupt changes as those of m. m. f., and will approach very closely to sine waves in the machine under consideration.

The final result of the analysis is thus to show that equal simple harmonic polyphase currents, when flowing in windings as above described, will produce an m.m.f. distribution approximately sinusoidal and revolving bodily around the gap periphery with a uniform angular velocity; or it might be said that a series of m.m.f. waves sweep around the gap. The degree of approximation of these waves to sine waves, and the smoothness of their rotation, increases with the number of phases and the number of slots per pole per phase.

A consideration of the current distribution as shown roughly by the crosses and dots on the axis of each of the curves (11a, 11b, etc.), shows that this is cyclic in character and that as a whole it is progressing along the gap periphery with the same velocity as that of the m.m.f. waves. The progression of the m.m.f. is of course merely the result of this current progression. The latter is the origin of the German term "Drehstrom," applied almost universally to three-phase motors and generators. The m.m.f. of the armature or secondary currents, will be considered later.

The effect of *Open Slots* on the field is obviously to introduce kinks into the flux distribution curves, there being a depression in the latter opposite each slot. If the armature also has open slots, the distribution of kinks will depend upon the relative position of the armature and field and their relative number of slots. The effect upon the time variation of flux at any point is to introduce very high harmonics.

Elementary Theory of Operation.

Consider now the interaction between a revolving field and the currents induced thereby in a short-circuited armature.

There are numerous varieties of short-circuited armature wind-

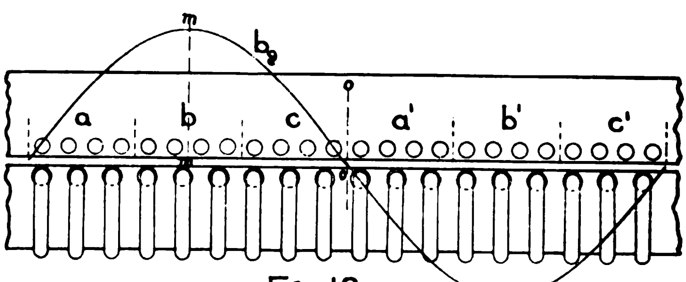


FIG. 12.

ings, some of which will be described later. For the present consider the type shown in the developed diagram of Fig. 12, where each active armature conductor forms part of a single closed loop surrounding the ring core, and is independent of the others.

Assume a constant,* uniformly revolving flux, distributed sinusoidally along the air gap.

Let $\omega_1 =$ the electrical angular velocity of the revolving field. Then $\omega_1 = 2\pi n$ where n is the frequency of the impressed currents.

Let $\omega_2 =$ the electrical angular velocity of the armature rotation. Then $\omega_1 - \omega_2 =$ the relative electrical angular velocity between field and armature, or what may be called the electrical angular velocity of *slip* between armature and field. As far as the armature currents are concerned, the result would be exactly the same if the field were stationary and the armature made to revolve backwards (counter-clockwise), with the electrical angular velocity $\omega_1 - \omega_2$.

Slip. The percentage which this slip velocity is of the field velocity, is usually called the ***slip***, and will be herein designated by the small letter s; we then have —

$$s = \frac{\omega_1 - \omega_2}{\omega_1} \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

When $s = 0$, $\omega_2 = \omega_1$, and the armature is said to be revolving synchronously, or in synchronism with the field.

When $s = 1$, $\omega = 0$, and the armature is at standstill; s may then be defined as the percentage by which the armature falls below synchronism.

Armature E. M. F. As the armature revolves backwards relatively to the flux, each armature conductor cuts through the flux and has generated in it an alternating e. m. f. with one complete cycle for each electrical slip revolution. The frequency of this armature e. m. f. is therefore equal to the number of electrical slip revolutions per second, namely, $\frac{\omega_1 - \omega_2}{2\pi} =$

* The induction motor is a form of transformer with a short-circuited secondary free to revolve, and as such there are three fluxes to be considered: the above considered mutual flux which crosses the gap and links with both the field (or *primary*) and the armature (or *secondary*) conductors, and the primary and secondary leakage fluxes linked only with their respective circuits. In a good induction motor the latter are comparatively small. Therefore, of the impressed primary e. m. f., much the largest part is consumed in balancing the e. m. f. induced by the mutual or gap flux; and with constant impressed e. m. f. the mutual flux will vary with varying current only in so far as the impressed e. m. f. is partly consumed by the primary resistance and leakage reactance.

sn. Designating this armature or secondary frequency by n_2,

$$n_2 = \frac{s\omega_1}{2\pi} = sn \quad . \quad . \quad . \quad . \quad . \quad . \quad (4)$$

The magnitude of the armature e. m. f. is proportional to the velocity with which the armature conductors are cutting through the flux, *i. e.* proportional to the *slip*, and is in form sinusoidal, since the flux distribution is sinusoidal. Designating the r. m. s. value of this e. m. f. by E'_2, we may write —

$$E_2' = Cs \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (5)$$

where C is the constant of proportionality, involving the r. m. s. value of the flux density, the length and peripheral velocity of the armature. It should be remembered that we are here considering the e. m. f. of only a single loop or conductor.

Thus both the frequency and magnitude of the armature e. m. f. are proportional to the slip s. This relation is very important and should be kept clearly in mind.

Armature Current. With a given e. m. f. E'_2, of frequency n_2, the phase and magnitude of the resulting armature current will depend upon the resistance and leakage inductance of the armature coil under consideration. The leakage inductance takes account of what is called the armature *leakage flux*, namely that flux which is due to the armature current and is linked with only the armature circuit, not with the main field circuit.

There are thus three e. m. f.'s acting in this closed armature coil; E'_2, the e. m. f. induced by the cutting of the main flux (corresponding to the impressed e. m. f. in a simple a. c. circuit), the reactive e. m. f. induced by the leakage flux, and the counter e. m. f. of resistance. Designate the armature current by I_2, and the armature resistance and leakage inductance by r_2 and L_2 respectively. Then the secondary leakage reactance is —

$$2\pi n_2 L_2 = s\omega_1 L_2 = s x_2 \quad . \quad . \quad . \quad . \quad . \quad (6)$$

where x_2 is the secondary leakage reactance when $s = 1$, *i. e.* at standstill. The armature current is then —

$$I_2 = \frac{E'_2}{\sqrt{r_2^2 + s^2 x_2^2}} = \frac{Cs}{\sqrt{r_2^2 + s^2 x_2^2}} \quad . \quad . \quad . \quad . \quad (7)$$

If we designate by θ_2 the angle by which I_2 lags behind E'_2, we have —

$$\tan \theta_2 = \frac{sx_2}{r_2} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (8)$$

Thus for a given machine, both the phase and magnitude of the armature current are determined by the slip, since all the other quantities involved in equations (7) and (8) are constants. (This includes the assumption of a constant flux, which is a rough approximation to actual conditions.)

For small values of s, *i. e.* for values of the armature speed which approach closely to the constant field speed, I_2 is practically proportional to s; but as s increases, the second term in the denominator of (7) becomes more important and I_2 increases less rapidly, until r_2^2 finally becomes negligible as compared with $s^2x^2_2$ and I_2 approaches its limit, $\frac{C}{x_2}$, see Fig. 13.

Armature Torque. Keeping the above relations in mind, investigate the torque producing value of the armature current for different values of s.

Referring to Fig. 12, imagine the flux and armature to be moving from left to right, but the armature less rapidly than the flux. The relative motion of the armature through the flux will then be from right to left.

Consider any one armature coil as it slips by the field with a uniform velocity. The e. m. f. induced by this motion will be sinusoidal since the flux distribution is sinusoidal, and *if* there were *no leakage reactance*, the current would be in phase with this e. m. f. In this case of *no leakage*, the current would reach its maximum value at the same instant at which the e. m. f. reaches its maximum value, namely when the coil in question is in the strongest part of the field (at m, Fig. 12, where the sine curve shows the flux distribution in the gap at the instant under consideration), and would reverse just as the coil was passing from the positive flux to the negative (o, Fig. 12).

The drag of the field on the coil at any instant is proportional to the strength of the current at that instant and to the

strength of the field in which it is located. Therefore, since the current and field reverse together, the drag will always be in the same direction, namely, the direction in which the field is moving.

In Fig. 14, curve I represents the flux distribution around the field periphery; curve II represents the current in the armature coil under consideration, when in the several positions along the field periphery. *E. g.* the maximum e. m. f. occurs when the coil is cutting through the strongest part of the field (*m*, Fig. 14), and since we have assumed that there is no leakage inductance there will be no lag, and the maximum current will occur when the coil is at *m*; similarly with the other points. Curve III is the product of I and II, and its ordinates are therefore proportional to the drag upon the coil in the several positions; the line $\overline{dd}$ shows the average value of this drag.

The drag or torque due a number of armature coils equally spaced, would be represented by the sum of several equally spaced overlapping curves, each similar to III. A little consideration will show that this sum is a constant quantity and may thus be represented by a straight line.

In this assumed case of no lag and constant flux, the torque is proportional to the current. Therefore, as the slip increases, the torque will also increase, and in the same manner as the current (see Fig. 13). But no armature is without leakage inductance and the resulting lag must be considered.

Effect of Lag upon Torque. A lagging current means a lapse of time between the occurrence of similar values of the e. m. f. and current, and during this lapse of time the armature coil has moved into a field of different density. *E. g.* the armature current does not reach zero until shortly after the e. m. f. has passed through zero, during which interval the coil has slipped back to some position such as *e*, (Fig. 14 and Fig. 15), and the current will be displaced relatively to the flux curve, (Fig. 15). The resulting torque curve is shown in III, (Fig. 15), from which it appears that the average torque is much reduced from what it was with the same value of non-lagging current. In fact, if

there were a 90° displacement between the current and flux curves, their average product would be zero. The effect of

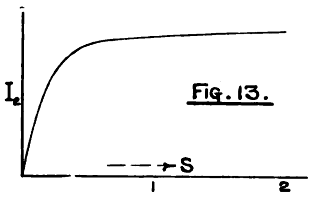


FIG. 13.

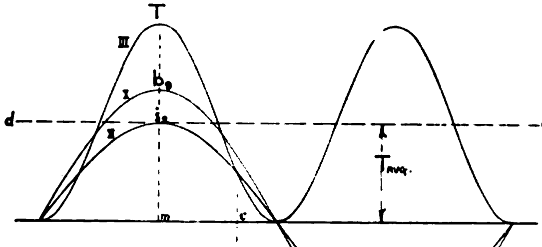


FIG. 14.

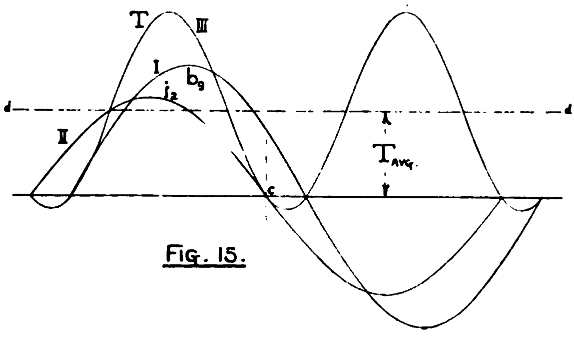


FIG. 15.

leakage inductance and the resulting lag of armature current is thus to diminish the torque producing value of the current.

When calculating the power in an a. c. circuit, it is found that the average value of the product of two sine functions of the same frequency is equal to the product of their r. m. s.

values and the cosine of the angle of phase displacement between them. Therefore the average value of the torque is proportional to the cosine of the angle between the current and flux curves (I and II, Fig. 15). But this angle is the angle by which the armature falls behind the revolving field during the lag interval, and is proportional to the rate at which the armature is falling behind (*i. e.* to the electrical angular velocity of slip), and to the duration of the interval. These two factors may be obtained as follows:

The frequency of the armature current is, $n_2 = \frac{s\omega_1}{2\pi}$ (See eq. 4). Therefore the time occupied by one complete cycle is $\frac{1}{n_2} = \frac{2\pi}{s\omega_1}$, and the time corresponding to the lag angle θ_2 is, $\frac{\theta_2}{2\pi} \times \frac{2\pi}{s\omega_1} = \frac{\theta_2}{s\omega_1}$ seconds. The electrical angular velocity of slip is $s\omega_1$, and the electrical angle of slip during $\frac{\theta_2}{s\omega_1}$ seconds is then,

$\theta_2 = \tan^{-1} \frac{sx_2}{r_2}$, (see eq. 8).

Thus the angular displacement of the current and flux curves (Fig. 15) is equal to the angle θ_2 by which the current lags behind its e. m. f. The cosine of this angle is,

$$\cos \theta_2 = \frac{r_2}{\sqrt{r_2^2 + s^2 x_2^2}} \quad . \quad . \quad . \quad . \quad . \quad (9)$$

Remembering that the average torque is proportional to the product of current, flux and cos θ_2, and that the flux is assumed constant, it appears that as s increases (*i. e.* as the armature slows down), the torque is effected in two opposite directions; increased by the increase in current and decreased by the decrease in cos θ_2.

This last effect may be explained thus: the increase in θ_2 allows the armature conductors to be carried farther back into the reversed field, introducing a negative torque period and thus reducing the average torque.

The combination of the above two opposing effects may be

more accurately analyzed by means of the algebraic statement of the relation involved.

Designating the average torque by $\underline{T}$ and the r. m. s. value of the flux density around the field periphery by $\underline{B}$ we may write —

$$T = C'_1 \, B \, I_2 \cos \theta_2 \quad . \quad . \quad . \quad . \quad . \quad . \qquad (10)$$

where C'_1 is the constant of proportionality.

Substituting for I_2 and $\cos \theta_2$ their values as given in equations (7) and (9), and combining the three constants $\underline{C}$, $\underline{C_1}$, and $\underline{B}$ into one constant C'_2 we have:

$$T = C_2 \frac{s r_2}{r_2^2 \times s^2 x_2^2} \quad . \quad . \quad . \quad . \quad . \quad . \qquad (11)$$

Strictly speaking we have been dealing with only a single armature coil, but equation 11 may be used to determine the torque due to any number of coils, by a proper change in the constant, C_2.

Analysis of Torque Equation. For very small values of s, $\underline{s^2 x_2^2}$ may be neglected, and (11) may be written, as an approximation,

$$T_{s \text{ small}} = C'_2 \frac{s}{r_2} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \qquad (12)$$

which is the equation to a straight line. If we plot s downwards from o' and ω_2 upwards from o, Fig. 16, the above mentioned straight line, $\overline{o'a}$, Fig. 16, will slope downwards from the horizontal by an angle ϕ_o such that

$$\tan \phi_o = \frac{r_2}{C'_2} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \qquad (12a)$$

In other words, the drop in speed, for a given torque, is proportional to the armature resistance. As s increases, the second term in the denominator of (11) increases more and more rapidly and soon predominates. Then r_2^2 may be neglected, and we have as an approximation for large values of s,—

$$T_{s \text{ large}} = C'_2 \frac{r_2}{s x_2^2} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \qquad (13)$$

which is the equation to a rectangular hyperbola with $\overline{o'o}$ and $\overline{o'x}$ as asymtotes. This is shown by the broken curve $\overline{c'b}$, Fig. 16. The actual curve lies between these two (o'a and c'b), and is shown full in curve I. This curve is sometimes called the mechanical characteristic or the speed characteristic, as it shows the relation between speed and torque or between slip and torque.

The connection between the torque curve and eq. (11) will become more clear by going back to equations (7) and (9) from which (11) is built up. (See also Fig. 13.)

As s increases from zero, I_2 increases at first practically in proportion to s, while $\cos\theta_2$ changes at first very slowly; *i. e.* the torque-increasing effect of the increased current predominates over the torque-decreasing effect of the increased lag. But as s continues to increase, I_2 increases less rapidly and $\cos\theta_2$ decreases more rapidly; *i. e.* the torque-decreasing effect of the increased lag begins to predominate and the torque decreases.

Maximum Torque. The value of s corresponding to the maximum torque may be found by placing $\frac{dT}{ds} = 0$ and solving for s. This gives:

$$s_{T\,max} = \frac{r_2}{x_2} \qquad \qquad (14)$$

Substituting this in (11), gives as the maximum torque:

$$T_{max} = \frac{C'_2}{2x_2} = \frac{C'_2}{4\pi n L_2} \qquad \qquad (15)$$

Thus the maximum or break-down torque is independent of the resistance, and inversely proportional to the leakage inductance of the armature and to the frequency of the primary polyphase alternating currents by means of which the rotating field is produced. This is one of the reasons why high frequency induction motors are relatively unsatisfactory, since, other things being equal, high frequency means relatively low break-down torque, T_{max}.

Equation (14) shows the interesting fact that the value of r_2 which makes the torque a maximum at standstill ($s = 1$) is, $r_2 = x_2$.

Starting Torque. A standstill s = 1 and eq. 11 becomes —

$$T_o = \frac{C_2 r_2}{r_2^2 \times x_2^2} \qquad \qquad (16)$$

For values of r_2 within the range of normal operation, r_2^2 may be neglected in the denominator and we have as a fair approximation:

$$T'_o = \frac{C_2 r_2}{x_2^2} \qquad \qquad (16a)$$

Equations 11 to 16 inclusive, show clearly the relation between some of the constants of the induction motor and its general characteristics of operation. There is one point, however, that needs a little explanation; it has been assumed that the flux (or, what is equivalent, the r. m. s. value B of the gap density) is constant, with constant impressed primary e. m. f. But as the primary current increases, the primary counter e. m. f. (to which B is proportional) differs more and more from the constant impressed e. m. f., because of the increased drop, due partly to the primary resistance but mostly to the primary leakage reactance, and although this decrease of B is small during normal operation, it becomes large at low speeds. Moreover, B is twice a factor in C_2.

The effect of the primary leakage reactance is thus to reduce the torque corresponding to any value of s, which is much the same as the effect of the secondary leakage reactance. Much of what is here said in regard to secondary leakage reactance will apply roughly, therefore, to the primary leakage reactance.

Secondary Resistance. Fig. 16. From eq. 12a, the droop of the speed torque characteristic is directly proportional to r_2; *i. e.* the smaller r_2 the better the speed regulation.

From eq. 14, the slip corresponding to maximum torque is directly proportional to r_2, and from eq. 15, the maximum torque is independent of r_2. Therefore the point m will move vertically in the figure as r_2 varies, the distance of m below $\overline{oX}$ being directly proportional to r_2, (eq. 14). In Fig. 16, the three torque curves correspond to values of r_2 in the ratio of 1, 2, and 4, as shown.

From eq. 16a, the starting torque is directly proportional to r_2 (for small values of r_2).

It thus appears that good speed regulation requires a small r_2 and a large starting torque requires a large r_2. Both of these requisites cannot therefore be inherent in the same machine, but they are usually secured by inserting an extra resistance in the secondary or armature circuit while starting, and cutting

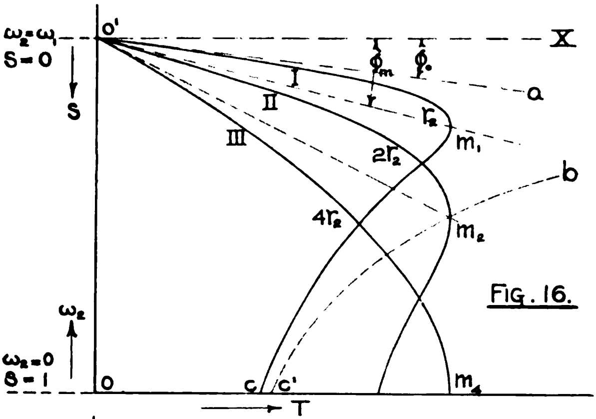


FIG. 16.

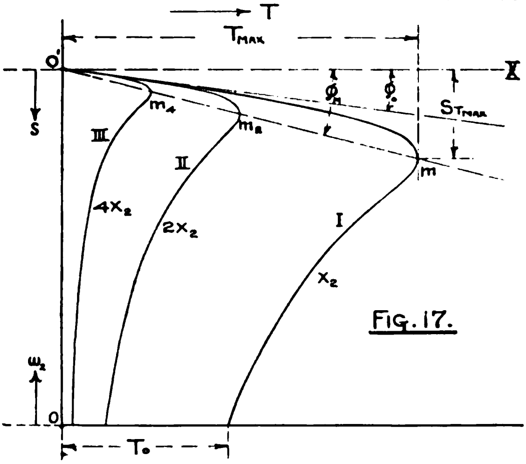


FIG. 17.

it out gradually as the speed increases, after much the same fashion as when starting a direct current motor.

This extra resistance may be external and connected to the armature with the aid of slip rings; it may be supported on the armature spider and be operated by means of a hand lever and sliding collar on the shaft, working a switch which also revolves

with the armature (this arrangement might be called a mechanical slip ring); or, while revolving with the armature, it may be cut out automatically by a centrifugal device set to operate at the proper speed.

Each of these devices involves a sacrifice of the beautiful simplicity made possible by the permanently short-circuited armature.

Leakage Reactance. From equation 15, the maximum torque is inversely proportional to x_2 and from equation 16a, the starting torque is, for small values of r_2, inversely proportional to the square of x_2. These points are shown in Fig. 17, where are drawn three speed-torque characteristics for three values of x_2, in the ratio of 1, 2 and 4 as indicated.

Dividing eq. 14 by eq. 15 gives —

$$\tan \phi_m = \frac{2r_2}{C_2} \qquad \qquad (17)$$

which is independent of x_2. Therefore all of the break-down points, m_1, m_2, etc., will fall on the same line, $\overline{om}$.

Another undesirable effect of the leakage reactance, which will appear more clearly later, is that it lowers the primary power factor.

It is thus eminently desirable on all accounts to reduce the leakage reactance to the lowest possible limit. A few of the obvious methods of reducing the leakage *inductance* are: reduce the length of conductor; reduce the number of amperes per slot in order that the leakage flux generated by one ampere may be linked with as few other amperes as possible; reduce the ratio of slot depth to slot width, in order to increase the reluctance of the leakage path; and use open rather than closed slots.

Frequency. Since x_2 is proportional to n, what has been said of x_2 applies with equal force to the frequency, and it is now apparent why high frequency induction motors possess much less desirable operating characteristics than those for low frequency.

Air Gap. Considering the induction motor from the transformer standpoint, and remembering that the flux is determined

by the impressed e. m. f., it is obvious that the primary circuits must carry exciting currents of sufficient magnitude to produce the necessary flux. Moreover, since the reluctance of the main magnetic circuit is mostly in the air gap, the exciting current will consist chiefly of a magnetizing component 90° behind the impressed e. m. f.

In order therefore to reduce this magnetizing current and thus to improve the power factor, the length of the air gap must be reduced to the mechanical limit.

Armature Winding.

The armature winding considered thus far consists of a number of independent coils on a ring core. The active part of each coil is that part lying on the outer surface of the core, across the periphery of the air gap, the inner part being necessary only as a means of completing the circuit. This method was illustrated because of its simplicity, but the end connections are too long, introduce too much resistance and leakage reactance, and involve too great a weight of copper.

There are several other methods of connecting up these active conductors, the most important conditions to be satisfied being that the minimum length of wire should be employed, and that all the conductors connected together in one circuit should lie in similar parts of the field, *i. e.*, they must be so situated that the e. m. f. induced in any one of them will always be in the same direction as that induced in all of the others at the same instant. This is also equivalent to saying that the torque due to the current in one of these conductors will be in the same direction as that due to the current in each of the others at the same instant.

Similars. When two active conductors are 180 electrical degrees (or any multiple thereof) apart, they are called similars; from which it follows that any two adjacent similars when connected together to form a loop, satisfy the above condition.

There are various other methods of connecting up these similars in short-circuited sets, but much the most common forms

of arrangement of the secondary active conductors are the following.

Squirrel Cage Secondary. In this case the secondary conductors consist of copper bars, round or rectangular, usually uninsulated, one per slot, and connected together at the ends by two copper rings, one at each end of the core, soldered (or screwed, or both) to the end of each active conductor.

This arrangement has a lower equivalent resistance of end connections for the same amount of copper than any other, and is ideal in its rugged simplicity.

Wound Secondary. It frequently happens, however, that it is desirable to introduce a resistance into the secondary for starting, or for speed control. In this case the conductors must be connected up in a comparatively small number of circuits or phases, in order to avoid complication due to many slip rings or other connections. As the three-phase winding gives the smallest number of leads in proportion to the number of circuits, this is ordinarily employed, the winding being carried out in any of the methods described for the primary, on pages 64 to 68.

The six belt (per pair of poles) drum windings are obviously the best. The objection to the three belt winding is similar to that explained in connection with its use as primary; namely, there is a large part of the time when some of the conductors of a belt are cutting the flux from one pole and the remainder cutting the reversed flux; also since the current must be in the same direction in all parts of a belt at any instant, some of this current is reacting on one flux and the remainder on the reversed flux.

This *differential action* in e. m. f. generation as well as in torque production is greater the greater the span (in electrical degrees) of a single belt. It is present in a six-belt winding to the extent of about 5% loss, but is entirely absent in the squirrel cage and where the winding is made up of independent sets of ***similars***.

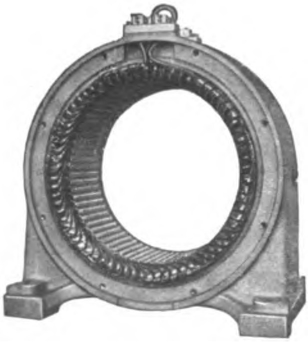
Fig. 18 shows a modern induction motor in various stages of construction. The primary has a three-phase lap winding

of form-wound coils in rectangular open slots, and the secondary a squirrel cage, made up of rectangular bars in partly closed slots and bolted to broad end rings with large radiating surface.

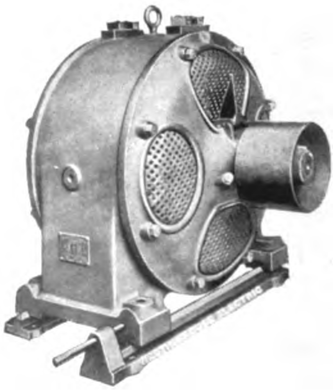
(To be continued.)

Cast-iron housing.

Primary ready for winding.



Primary completely wound.



Secondary core.

Secondary complete.

Figure 18.

HARVARD ENGINEERING JOURNAL.

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GILBERT SIMERALL MEEM, A. B. '02.

IT is with great regret that we announce the death of Mr. Gilbert Simerall Meem, Jr. '02, of Seattle, Washington. He was editor-in-chief of the Journal in 1902 and, having been elected last spring president of the Harvard Engineering Society

he was associated with the retiring 1903 Board as an *ex-officio* member.

Mr. Meem received the degree of A. B. in 1902, and the following year he took courses under the Division of Engineering, hoping to take the Electrical Engineering degree this year. Last summer, however, he entered the employ of Stone & Webster of Boston in the electrical department of one of their stations at Tacoma, Washington. This work was so much to his liking that he later accepted a position with the Seattle Electric Company. He intended to continue at this practical work for a year, and then return to Harvard to finish his course. While thus engaged at Seattle he was suddenly taken ill with symptoms of ptomaine poisoning which, in a few days, developed into appendicitis from which, after a fruitless operation was made to save him, he died on January 28 of this year.

The Journal owes much to Mr. Meem. During the year he was editor-in-chief, he led in no uncertain way in establishing its permanency, and by his foresight and executive ability set higher standards, than had been before attained.

Graduate Notes.

R. I. Wilby, '01, is assistant engineer with the P. R. R. Chicago.

H. S. Pollard, '02, is a special apprentice in the Motive Power Department of the C. B. & Q. R. R.

M. Bartlett, '00, is with the C. B. & Q. R. R. Freight Department, Chicago.

J. H. Libbey, '98, is mechanical engineer of Boston & Northern and Old Colony Street Railway Companies.

Architectural Notes.

In order that it may represent freedom in the circulation of ideas on architectural subjects, the JOURNAL invites communications on technical and aesthetic matters. The magazine will be

glad to publish such of these as seem of enough interest, but will not hold itself responsible for any ideas which may be expressed.

There is for instance a difference of opinion as suggested in the article in this number, with regard to the importance to be given to the study of the orders. There are differences regarding the qualities of fire proofing material used in building, the question of propriety of using the modern French style to express the conditions of life in New York City, the question of the ethics of architectural competition, or the discussion as to whether architect's ideas should be presented by drawings or models or both. Then as to the comparative importance of English and French Gothic architecture for instance. These and many more such interesting matters invite discussion which is always stimulating and which, if carried far enough, always gives some satisfaction if not the exact truth. That something of this life may find its way into the pages of the JOURNAL is earnestly hoped for by the editors.

In order to distinguish graduates in Architecture in the University from those in the academic department, who have perhaps taken some courses in architectural history or design but not completed the full course, the letter A will be used after the names of those men who have taken the degree in architecture.

L. P. Burnham, '02, A, the holder of the Nelson Robinson Jr. Travelling Fellowship in Architecture for 1903–04 is at present in Rome, as is also E. T. Putnam, '01, who was a student in the Department of Architecture during 1901–'03.

E. T. P. Graham, '00, A, the holder of the Travelling Fellowship in 1901–'02, who has been in independent practice during the past half year has, with G. S. R. McLean '00, A, prepared plans for an important building near Harvard Square.

G. S. Parker, '00, A, who has recently returned from Paris, is in the office of C. A. Platt in New York who is doing so much to develop and domesticate the fine old Georgian

style in this country, in connection with its natural adjunct the formal garden.

Of those men who have studied for longer or shorter periods in the Department of Architecture, the following are now in Paris: F. B. Hoffman, '03, R. P. Bellows, '99, and G. G. Hubbard, '99. C. F. Gould, '98, after five years at the Ecole des Beaux Arts is now in the office of Messrs. McKim, Mead and White in New York City.

Edward B. Lee, '00, A, holder of the Travelling Fellowship for 1902–'03, has nearly completed his work at the Ecole in Paris and expects to return to this country in May.

Mr. Emil Lorch, A.M. '03, who was assistant in architecture in the Department last year, is Assistant Professor of Architecture in the Drexel Institute in Philadelphia.

EAST FACADE OF THE HARVARD STADIUM, NOVEMBER, 1903.

HARVARD ENGINEERING JOURNAL

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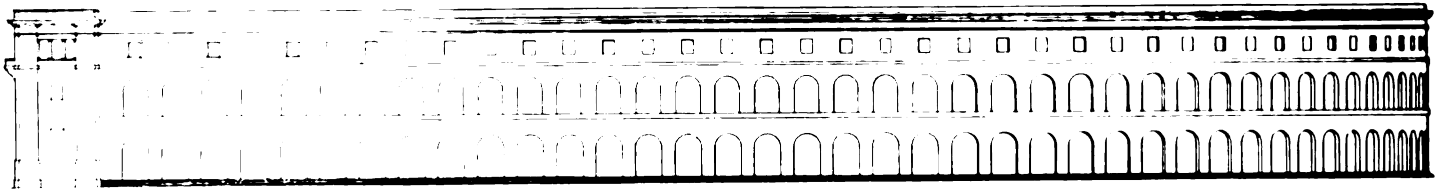
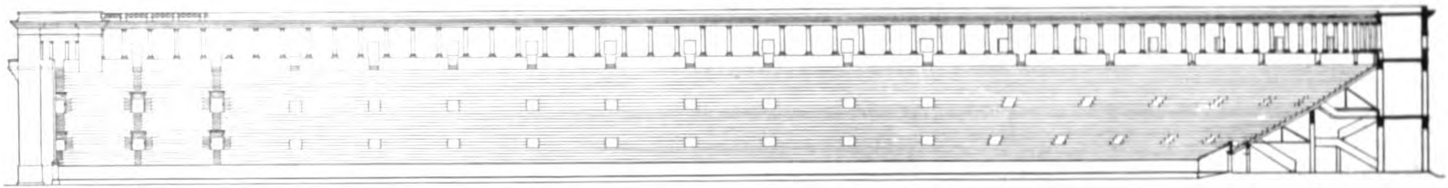
ORIGIN OF THE HARVARD STADIUM.

By I. N. Hollis, Professor of Engineering, Harvard University.

The development of Soldiers Field was held back for many years by the old wooden bleachers. Nothing final in the way of grading and filling the marsh could be accomplished so long as they remained, and the Athletic Association became an object of criticism for allowing them to remain. The President in one of his reports remarked that the grounds could not be made beautiful so long as those squalid banks of seats were permitted to deface them. A public duty rested upon Harvard to make the playground as attractive as possible, especially as it formed a natural part of the great Metropolitan Park System. It will eventually be connected with Boston and the suburban districts by the Charles River boulevard, and when the dam is completed, it will become one of the principal features of the great fresh water basin reached by pleasure craft of all kinds.

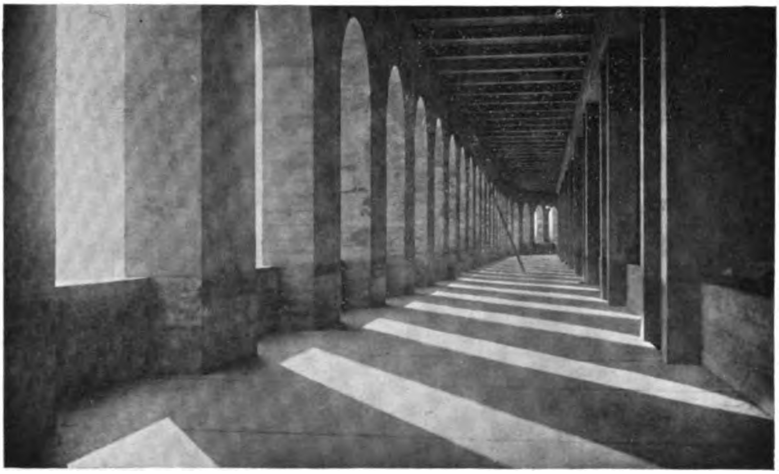
It was, however, not so much the unsightliness of the wooden seats which formed the objection to them, as the yearly problem of safety. The seats were of wood, and therefore more or less dangerous to life with the great crowds coming to the games. The risk of fire was always present, as was demonstrated last spring in the burning of the seats behind the back-stop of the baseball field. There, a grand stand loaded with thousands of spectators took fire and burned to the ground before the fire


SIDE ELEVATION


LONGITUDINAL SECTION

SIDE ELEVATION AND LONGITUDINAL SECTION OF THE STADIUM AS IT WILL APPEAR WHEN FINISHED.

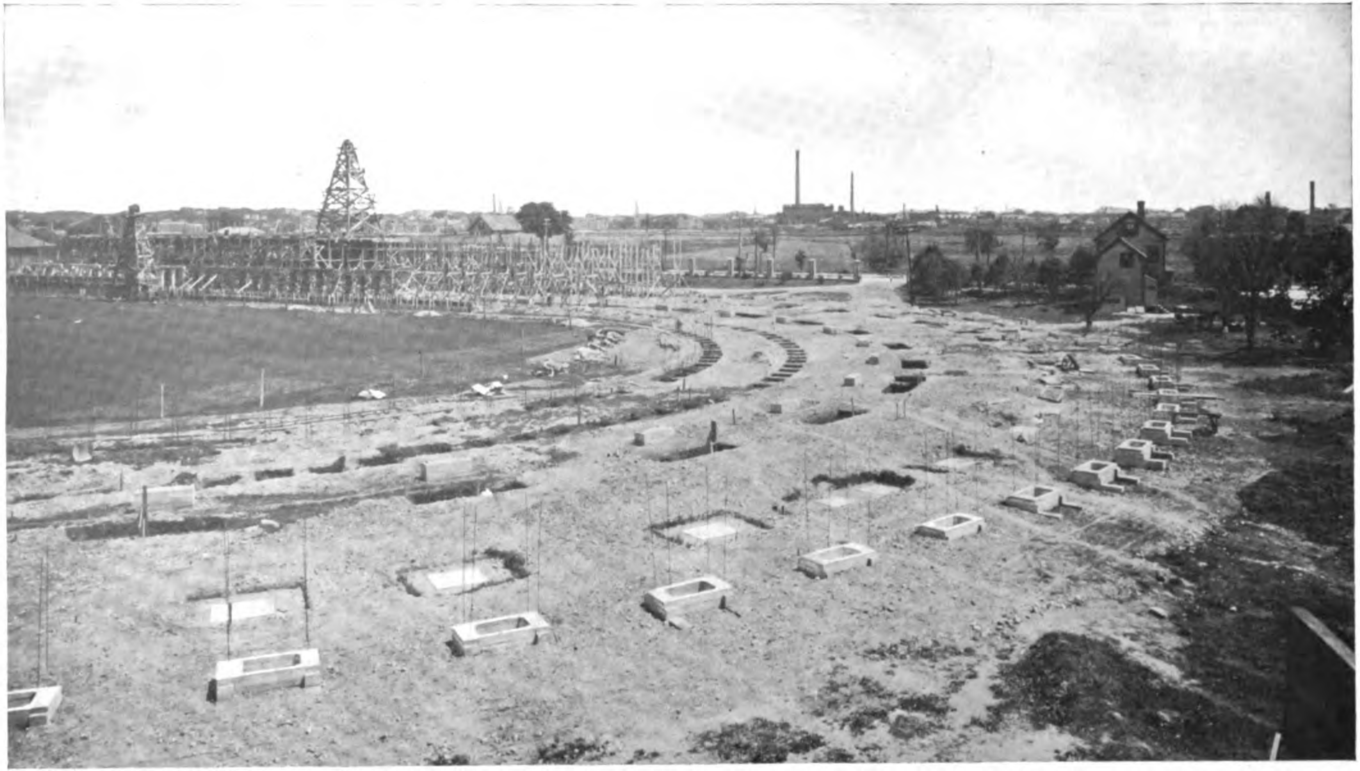
engines could reach the Field. Fortunately, the people were gotten out of the seats into the open space of the diamond without injury. A panic was narrowly averted by the presence of mind of an usher, who forcibly restrained one of the spectators from spreading the alarm of fire. One has only to imagine what might have happened in case the field had been entirely enclosed, as the gridiron is, and the spectators had numbered 30,000 or



EAST MEZZANINE PROMENADE.

40,000 to realize the serious risk in seating people upon great piles of dry lumber where smoking is permitted.

The Harvard Athletic Association has for many years minimized the danger as much as possible at all the large games by having firemen, and in some cases a fire engine, on hand to deal promptly with an incipient blaze. There have been half a dozen which might have developed into serious fires. It is not commonly known that the earlier amphitheatres built by the Romans were of wood, and that these were often destroyed by fire. The largest, that at Placentia, was burned. According to the "Encyclopaedia Britannica," a wooden amphitheatre erected at Fidenae in the time of Tiberius gave way under a great crowd,

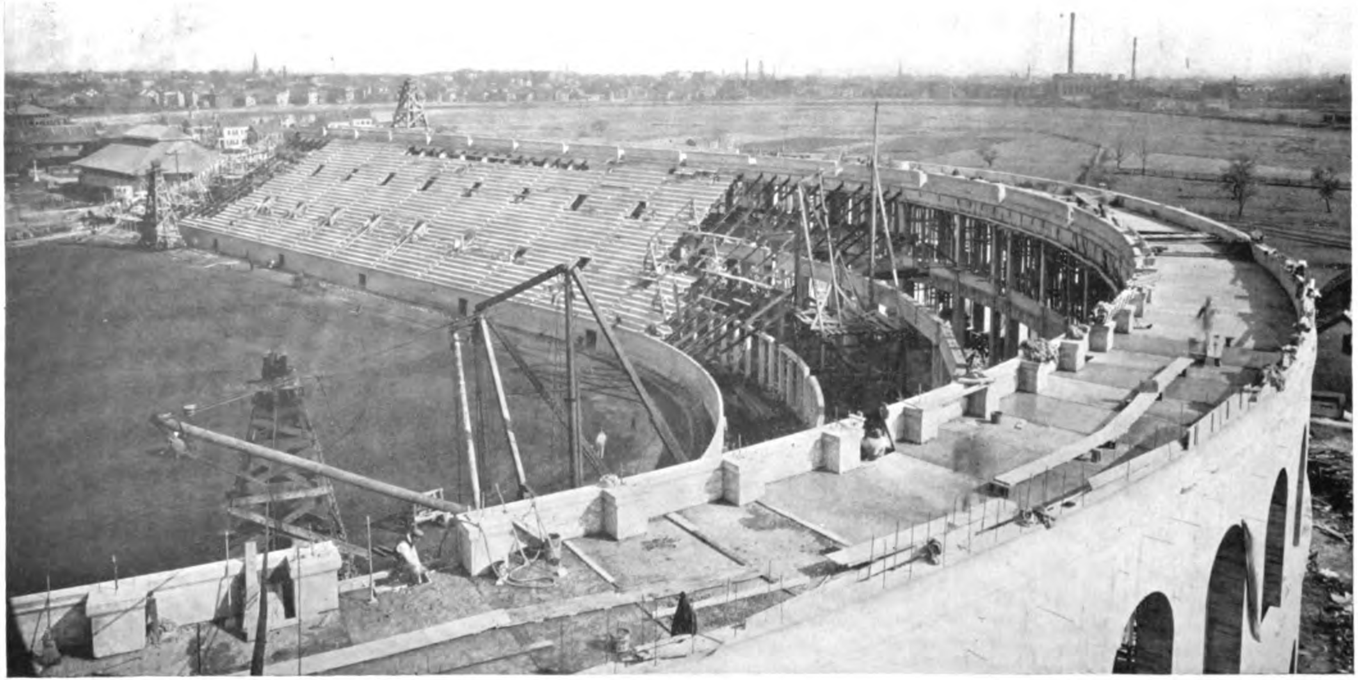


FOUNDATIONS, AUGUST, 1903.

and 50,000 people were killed or injured. A number of such disasters, combined with the probable scarcity of timber, led undoubtedly to the substitution of stone, brick, and cement for less enduring materials.

The second danger from wooden seats, that of collapse, springs from the nature of fastenings, which often lead to unexpected failures. The wood naturally decays around iron nails, and the decay is likely to be hidden. Added to which, in many temporary stands, there is a strong temptation to scant the materials. Parts of several grand stands have collapsed within a few years, notably one in Scotland, where a crowd of spectators were watching a football game. With proper inspection, the risk of breakdown is not great; at the same time, timber decays rapidly and constant vigilance is necessary to prevent accident.

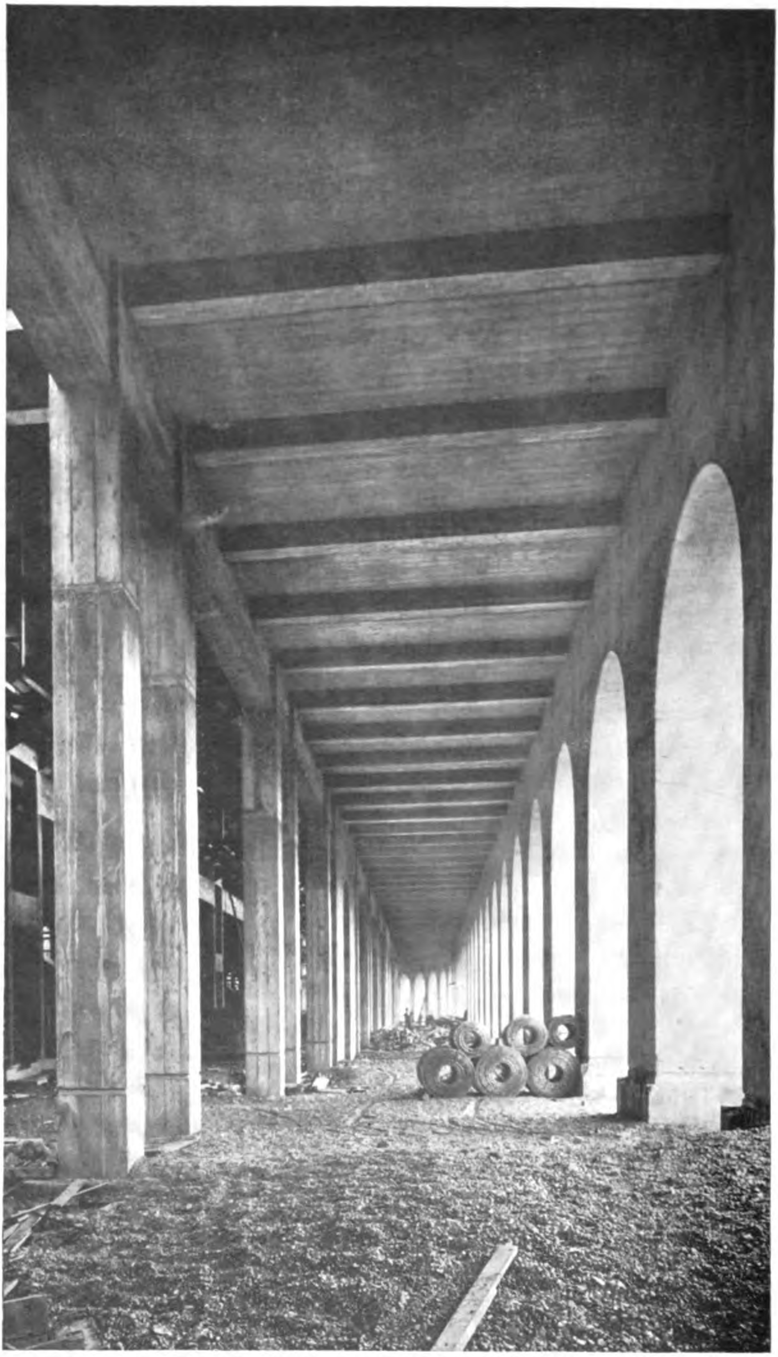
Another important consideration in connection with the Harvard bleachers might be discovered in the Graduate Manager's annual reports; that is, the great cost of maintenance of wooden bleachers. The yearly outlay for repairs amounted to not less than $1000. Wooden seats as ordinarily constructed are good only for about ten years, after which careful inspection is impracticable without taking down parts of the structure, entailing inordinate expenditures for replacements. There have usually been on Soldiers Field 16,000 permanent seats. Temporary stands have been erected for great games, when there was a demand for them. The cost of wooden seats to last for ten years is about $1 per seat; in all, this amounts to $16,000 for the Soldiers Field bleachers. The interest and repairs, including a yearly sinking fund for replacement, amounts thus to about $3500. The temporary seats, which can usually be put up and taken down in a few days, cost on the average 54 cents a seat. Taking into account 19,000 temporary seats for the Harvard-Yale game every second year, we must add to the above interest and repairs another sum equal to $4630. The total annual outlay for wooden seats thus mounts up to $8000, which is the interest on $200,000 capital. This has formed one of the great drains upon gate money, and has led to a feeling that the yearly expenses ought to be lessened in some way, even though the first cost was large.



EAST WING UNDER CONSTRUCTION.

In the discussion of the stands for athlectic purposes, the minds of many good friends of the University have been made uneasy at the thought of giving outdoor sports a more permanent form and one which seemed to offer to the public an annual spectacle out of proportion to their importance in a great seat of learning. This thought springs mainly from the annual football game, and many have lost sight of the fact that rowing is more open to the public than football. It demands much more time in preparation and the races have to be rowed in localities where every one can see them. The football games are attended so largely by the colleges whose teams are on the field that the general public forms only a small percentage of the spectators. During the past fall there were undoubtedly seats to be had from speculators and from ticket agents before the Harvard-Yale game, but when we consider that upwards of $12,000 was sent back to graduates and students whose applications could not be filled, we have a right to say that there was no public sale, and that the game could not be regarded as a public spectacle, open to those outside of the University. It is more in the nature of a contest intended to bring together at least once a year the friends of the universities whose teams are on the field. On the other hand it has been claimed by the believers in athletic sports and in intercollegiate contests, that they ought to be placed on a recognized and permanent basis, as the only method of controlling them properly. That there is a basis for this claim is shown in the gradual improvement of the sports as committees have obtained effective supervision of them.

There is much to be said on this general question, but the Harvard Athletic Association was in the face of a question which had to be decided,— What was to be done about the old bleachers? The decision to replace them by something fireproof, safe, and sightly, seems entirely justified. This is naturally part of the development of Soldiers Field. The acceptance of Soldiers Field twelve years ago implied a willingness on the part of the Corporation and the Faculty to put athletic sports upon a permanent basis and to give every student an opportunity to spend part of his time at college in outdoor games.



WEST ENTRANCE PROMENADE, NOVEMBER, 1903.

Many of the graduates will doubtless remember a very attractive perspective of the Field and of the improvements proposed by Messrs. Peabody & Stearns. The original drawing has been hanging in the Locker Building for many years. It contains the first suggestion of a stadium and of seats of a permanent form. The main reason why it was not carried out was that it required the placing of the gridiron, the track, and the diamond on the same central axis. There was not room on the Field for this, as it was thought to limit the out-field for baseball. Added to this objection, the subsequent building of the driveway contracted the space still more, and made it necessary to have a complete new plan of the Field. To the end of having something to work towards in the future development of the Field, Mr. F. L. Olmsted prepared several studies of the problem, and finally one was adopted that seemed eminently satisfactory. From this all new buildings are to be located, and from it the Stadium was laid out.

Our first experience with permanent seats was on Holmes Field, where several large steel bleachers were erected in the spring of 1897, made to hold several thousand people. They were subsequently moved to Soldiers Field, where they now stand, forming the seats for baseball. On them the seats proper are made of wood, supported by steel columns and trusses. They have been useful and safe, but the cost of maintenance has been unduly great, chargeable mainly to paint for the metal parts. At the end of seven years the wood is beginning to require renewal, and within a few years a large sum must be expended on them for repairs.

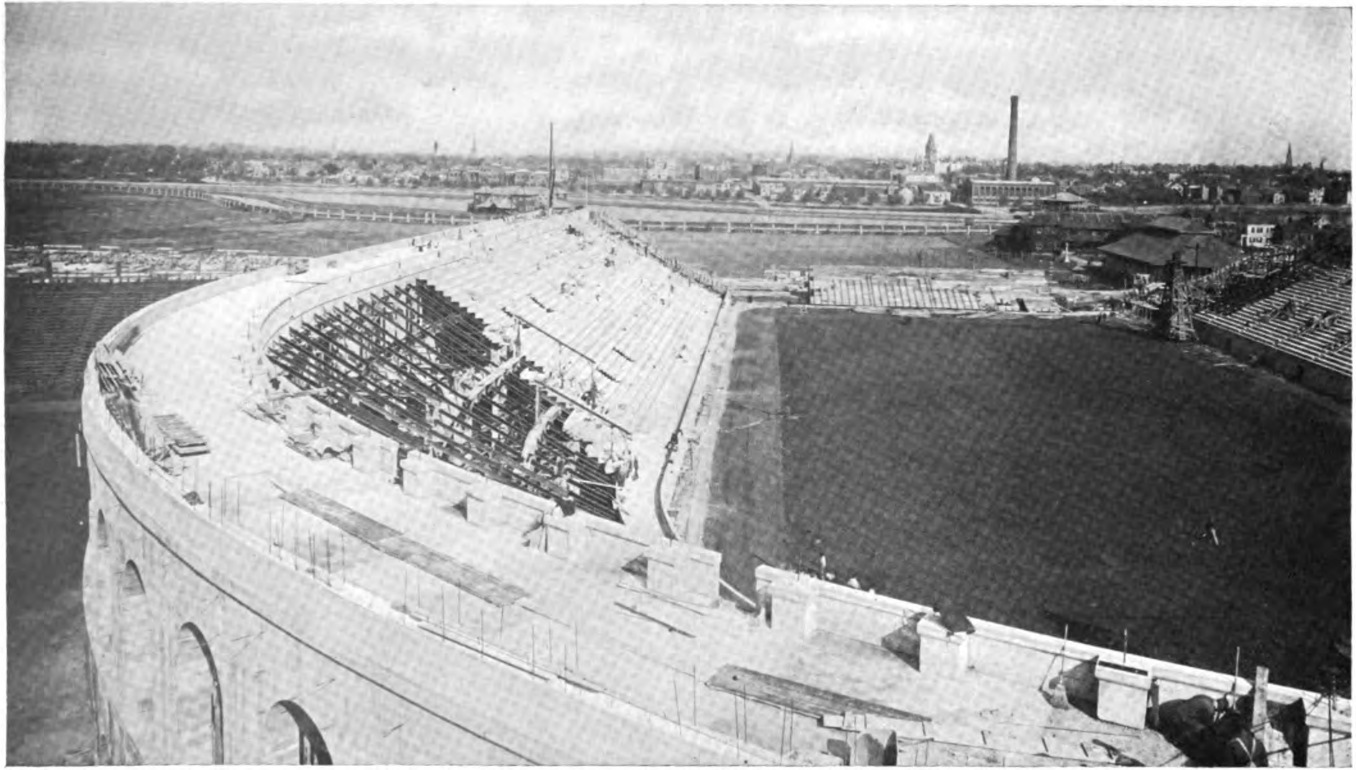
After it was decided to make the new stands fireproof, the nature of the materials was practically settled by the cost of construction. No other material but concrete with a small amount of steel could have been chosen for the means at the disposal of the Association. Stone and brick could not be considered. It was well understood that the use of concrete for out-of-door work in a New England climate was experimental, although this material has been extensively used elsewhere, in Europe and in the United States. Throughout the West nothing is thought of putting up buildings and bridges of

concrete, and experience has seemed to demonstrate its strength and durability.

As a method of testing the concrete effectively, and also for cheapness, the Soldiers Field fence was constructed a number of years ago almost entirely of concrete. The posts and beams were put in place by ordinary laborers, and the surfaces were subsequently picked to destroy the marks of the molds. There are about 6300 feet of this fence, and the frost has not seemed

EAST WING DURING THE DARTMOUTH GAME,
NOV. 14, 1903.

to affect it more than ordinary masonry would be affected by winter weather. This test, lasting over a series of years, while not finally conclusive as to the effect of time upon concrete, gave good reason to suppose that if well designed and constructed it would be amply able to withstand the New England winters. It is quite equal to many of the common building stones.



WEST WING UNDER CONSTRUCTION.

Another series of tests was undertaken in the laboratory by casting a dozen beams in the shape of the seat slabs and then breaking them in the large testing machine. The results were instructive and valuable, and assisted materially towards deciding for concrete as the principal material for tlie Stadium. It is sometimes erroneously supposed that concrete is not reliable. While it does vary in strength, there is no reason why it should not answer for all purposes even better than limestone. The method of handling the ingredients and the care taken in mixing them has all to do with the results, if the cement is of good quality. For the Stadium, Portland cement only was used, and the proportions of the materials were: one part of cement, three parts of sand, and five to six parts of broken stone, principally Roxbury pudding stone. The method of building consisted of putting up wooden molds, into which the concrete was poured. Every column and beam and all the walls had twisted steel rods imbedded in them, as a means of preventing cracks due to shrinkage. The removal of the wooden molds has in all cases left a perfect copy of the wood, and further treatment of the outside is made necessary to remove all evidence of joints and cracks as well as the grain of the wood. The seats were cast separately and were put in place upon steel girders, just as stone would be laid. They were really artificial stone, with steel netting imbedded in them to prevent cracks.

The design of the Stadium was begun several years ago by Prof. L. J. Johnson, upon lines laid down by the Athletic Association. A number of careful studies of steel supports and of the arrangement of entrances and seats were prepared in order to decide upon the most economical plan of building. The aim at first was to reproduce the steel stands built upon Holmes Field, substituting only concrete slabs for the planks used in the seats and treads. The plans went so far as to obtain prices on the steel work, but were abandoned finally in favor of a design which consisted almost entirely of concrete. The first cost of building in steel would have been less than in concrete, but the annual cost of maintenance would have been considerably greater. The difference of first cost was not great enough to justify a

steel structure. It was decided to have all supporting parts, such as walls, columns, floors, and arches, of concrete, while all inclined trusses, forming the immediate support of the seats, should be of steel. This seemed on the whole the best arrangement, as the steel underneath the seats would be fairly protected from the weather.

After the engineering details had been worked out, the whole was submitted to Mr. C. F. McKim for criticism and modification, and drawings were made under his direction by Mr. George B. de Gersdorff. These related to the general appearance of the structure and served to convert the design from one whose engineering features were ample to guarantee strength, into one pleasing to the eye. The working drawings were subsequently completed on Soldiers Field by Prof. L. J. Johnson, with Mr. J. R. Worcester as consulting engineer, but Mr. de Gersdorff's outlines were carefully followed. The seating arrangement was studied out with a view to keeping the spectators off the field, and also to give everyone an equally good view of the track and gridiron. To this end, the stairways led up from the rear through openings, and the seats were placed on three different slopes with the steepest at the top. The adoption of a single curved end with two straight sides, following the Greek plan, was made necessary by the track with its 220-yard straightaway. It is not intended here to give a full description of the Stadium, as the photographs serve to make that plain. However, it seems well to state some of the leading features. The dimensions are 576 feet by 420 feet, enclosing a field whose over-all dimensions are 481 feet by 230 feet.

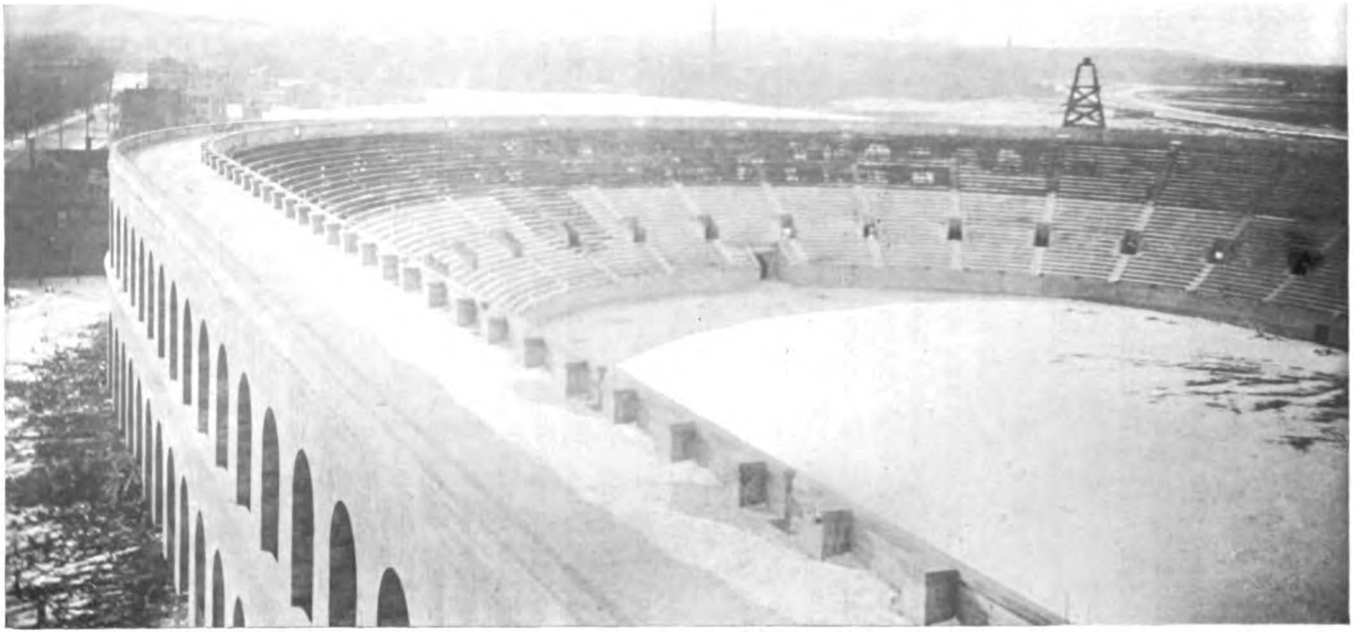
The distance between the front parapets is thus 230 feet. The two promenades in the rear are placed one above the level of the upper seat, and the other about midway between that and the ground. They are intended to be main arteries for leaving the seats after a great game, and they will be much used during the intervals between the parts of a game for the recreation of spectators. There will be over the upper promenade a roof, open towards the field and closed except for a few small windows towards the outside view.

MORNING OF THE YALE GAME, NOVEMBER 21, 1903.

Many questions have been asked about the actual seating capacity of the Stadium, and much misinformation on the subject has been circulated by the newspapers. The structure is divided into 37 sections: each section has 31 rows of seats; on the straight sides 20 or 21 persons can be placed in each row, on the curved end the number varies from 14 up to 26. The seating capacity, therefore, of that part on which stone seats are placed is either 21,000 or 23,000, dependent upon the way people are arranged. At the Yale game there were about 23,400 on the stone seats. It is possible, by the addition of some small temporary wooden seats on the top promenade and in front of the lower parapet wall to increase the number of spectators within the structure to 35,000. In case there are temporary seats across the open end, the number accommodated can be brought up to nearly 40,000. There were in all 38,300 at the Yale game; besides these there were others on the side lines and about the ends.

A number of uses have been suggested for the space beneath the seats. Ultimately, dressing-rooms may be added, and numerous handball courts could be built. The first addition will probably be a rifle range, as 130 yards can be found entirely free from obstruction and located in such a way that by no possible chance could a passer-by be injured. The present use of the grounds will be for football, the track sports, and for lacrosse. It was not possible to place the diamond on the field on account of the track. Those who recall the diamond as it was on Holmes Field will understand the danger to a runner who is trying to look at a ball and at the pole of a track. Besides this, it was not necessary to have all the fields in one place. There is plenty of room for all the sports on Soldiers Field without unnecessary crowding.

The work was begun on June 22 by the removal of the old baseball stands. The foundations were dug early in July, and that part of the columns above ground began to appear on July 28. It was necessary to push the work rapidly in order to be able to use the seats for the last games of the fall season. This was accomplished, although the structure was not completed.



THE HARVARD STADIUM IN THE WINTER OF 1903-04.

The estimate of the entire amount of concrete necessary to make the Stadium architecturally complete was 250,000 cubic feet. By Nov. 15, 200,000 cubic feet were in place, thus leaving about one fifth to be laid in the spring.

The decision to build during the past summer was hastened by the condition of the old bleachers, which were looked upon as under suspicion. It was a question of only a year before they would have to be torn down and replaced under any circumstances. Furthermore, it was hoped that part of the money going into temporary seats to provide for the large number of spectators at the Yale game could be saved.

The Athletic Association had been saving money for years to replace the wooden stands, and there was $75,000 in the treasury last spring. It was known that this fall would bring that up to $100,000, nearly half enough, according to the estimate, to build the stands. The Class of '79 stepped in at an opportune moment and by a gift of $100,000 not only enabled the Association to begin work at once, but to begin work upon a plan architecturally good. As the work progressed, it was very soon discovered that the estimates were low, in part due to the fact that they had been based upon a smaller amount of cement and concrete than was actually used, and in part the deficiency was due, also, to a real improvement in the design, by Mr. de Gersdorff and Prof. Johnson. The exact additional amount required to complete the structure is not now known, but it is hoped that it may not much exceed $50,000. This has been obtained on a guarantee loan, to be paid from year to year by the Athletic Association.

The method of doing the work was somewhat unusual, as on account of its character contractors could not bid without adding a large margin to their estimates to provide for unexpected contingencies. As finally arranged, the work was done by the Aberthaw Construction Company, who carried out the plans of the Athletic Association under Prof. Johnson's supervision, and also acted as agent for the Association in the procurement of materials and labor. The money for the work and materials was paid over weekly by the Treasurer of Harvard College, in whose custody it had been originally placed.

Before deciding definitely upon the location of the stadium the Athletic Association had purchased two pieces of property on the south side of the Field, thus surrounding it entirely by streets and public reservations. The future development ought to be carried out upon attractive and wise lines. Every year the gate money should pay for some permanent improvement, which should follow a definite policy. Thus, in ten or fifteen years, Soldier's Field will become one of the most attractive parts of the University and of this region.

MATERIALS AND DESIGN OF THE HARVARD STADIUM.[1]

By Lewis J. Johnson, Asst. Professor of Civil Engineering, Harvard University.

The Stadium is a masonry structure of an unusual character. It is unusual not only in its purpose and general outlines, but in the nature of the material of which it is constructed. This material, steel-concrete, calls for correspondingly novel treatment in its design. The character and methods of the design being so largely dependent upon the material, it is desirable to begin by explaining what is meant by steel-concrete, and comparing it with the more familiar forms of masonry.

Masonry is used in the Stadium as elsewhere in order to gain permanence and beauty. In the Stadium, as is usual in masonry buildings, certain parts intimately connected with the floor system are of steel.

The familiar forms of masonry — stone, brick, or terra cotta — consist of more or less accurately shaped blocks carefully laid in place one at a time, the joints being filled with mortar, every individual block and joint receiving the close attention of a skilled workman.

Concrete, the type of masonry used in the Stadium, consists of an immense number of stone blocks of small and varying sizes incorporated into a solid mass, by mixing them with the requisite amount of mortar. This mass is dumped, a wheelbarrow load or more at a time, into moulds, where it solidifies into masses of any desired form. This form may be a bridge abutment, or pier, an arch for a railway bridge, or a wall, girder

[1] This article is to a large extent taken from a paper presented by the writer to the Boston Society of Civil Engineers, Dec. 8, 1903, and printed in full in the Journal of the Association of Engineering Societies for June, 1904. Many of the cuts and all the working drawings here shown were made available to this Journal through the courtesy of the Association of Engineering Societies.

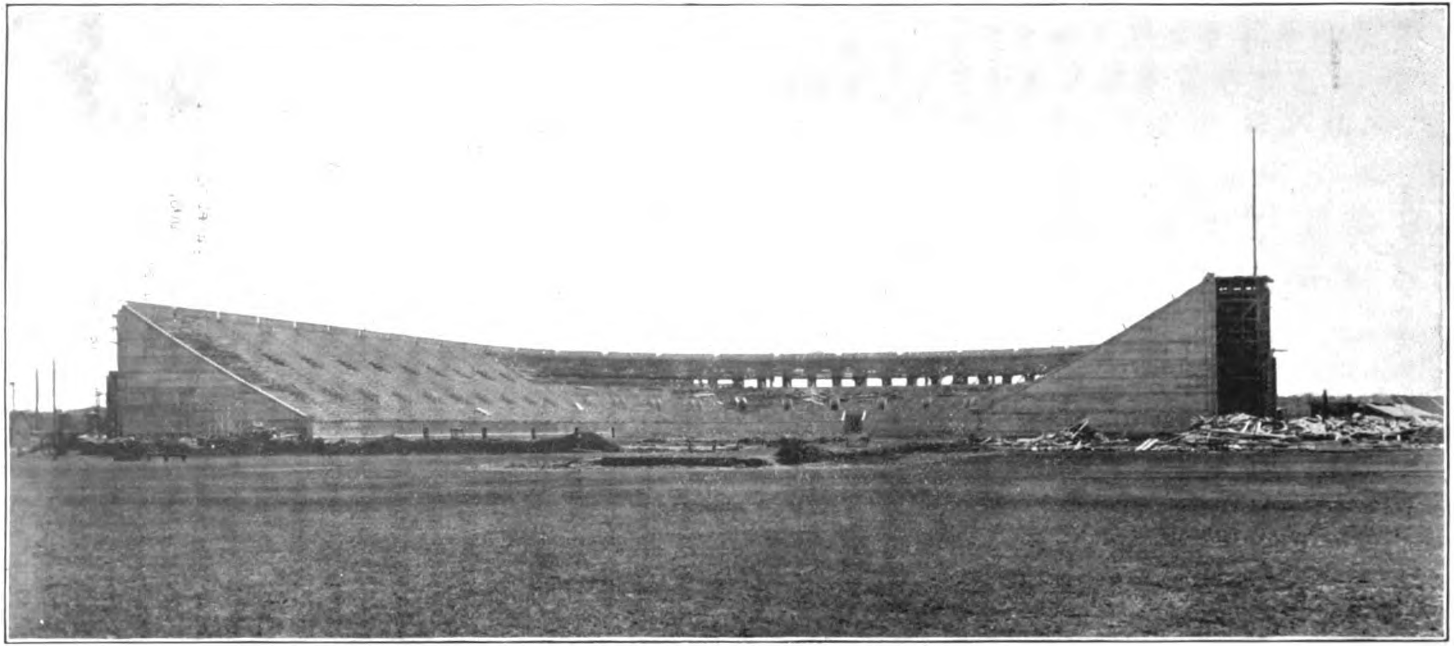


FIG. 1.—THE STADIUM IN APRIL, 1904, WITH SOME OF THE TEMPORARY WOODEN SEATS REMOVED TO MAKE WAY FOR THE PERMANENT SEATS.

or parapet. The only skilled labor required is in the construction of the moulds. No more attention is given to the preparation of the stone than is given to preparing stone for use in macadamizing a road. In fact, stone in shape for one of these purposes would be equally acceptable for the other — though the kind of stone best adapted for one may not be the one best for the other.

The mortar in concrete is composed of hydraulic cement (for important work above ground, usually of the grade known as Portland cement) and sand. The mortar may be made and mixed with the stone by the same operation. The proper proportions of dry cement, dry sand and broken stone are commonly dumped into the mixer; water is added, and the whole mass turned over and over, becoming moistened and mixed at the same time. On being dumped from the mixer, it is ready to be wheeled to the moulds.

In a word, all masonry is a mass of stone, bricks or terra cotta made into the desired shape with the voids and joints filled with mortar. In ordinary masonry, the joints are filled *one at a time*, in concrete a much larger number of voids are filled — but *many at a time* by the operations of merely mixing and stowing.

First class concrete is rated by engineers as safe under loads which would be entrusted to no other grade of masonry save the best limestone and granite ashlar. Moreover its hardening is a process which goes on indefinitely, so that for several years at least the older it is the stronger it is.

None of these classes of masonry is suitable for use where it will be subject to bending. Neither brick nor stone masonry can be made to resist bending to any great extent. Stone lintels may span small openings, but if the opening is one of any magnitude, the arch must be resorted to. Concrete, however, from its mode of preparation can be made to include steel bars of any amount and in any location where it may be needed to prevent cracking — whether the cracking be due to bending, as on the under side of a beam, or to shrinkage in setting, or from cold weather. Steel is effective in this way by virtue of the adhesion of the Portland cement. The resistance of the rod to slipping

FIG. 2.—WESTERN FAÇADE OF THE STADIUM IN APRIL, 1904.

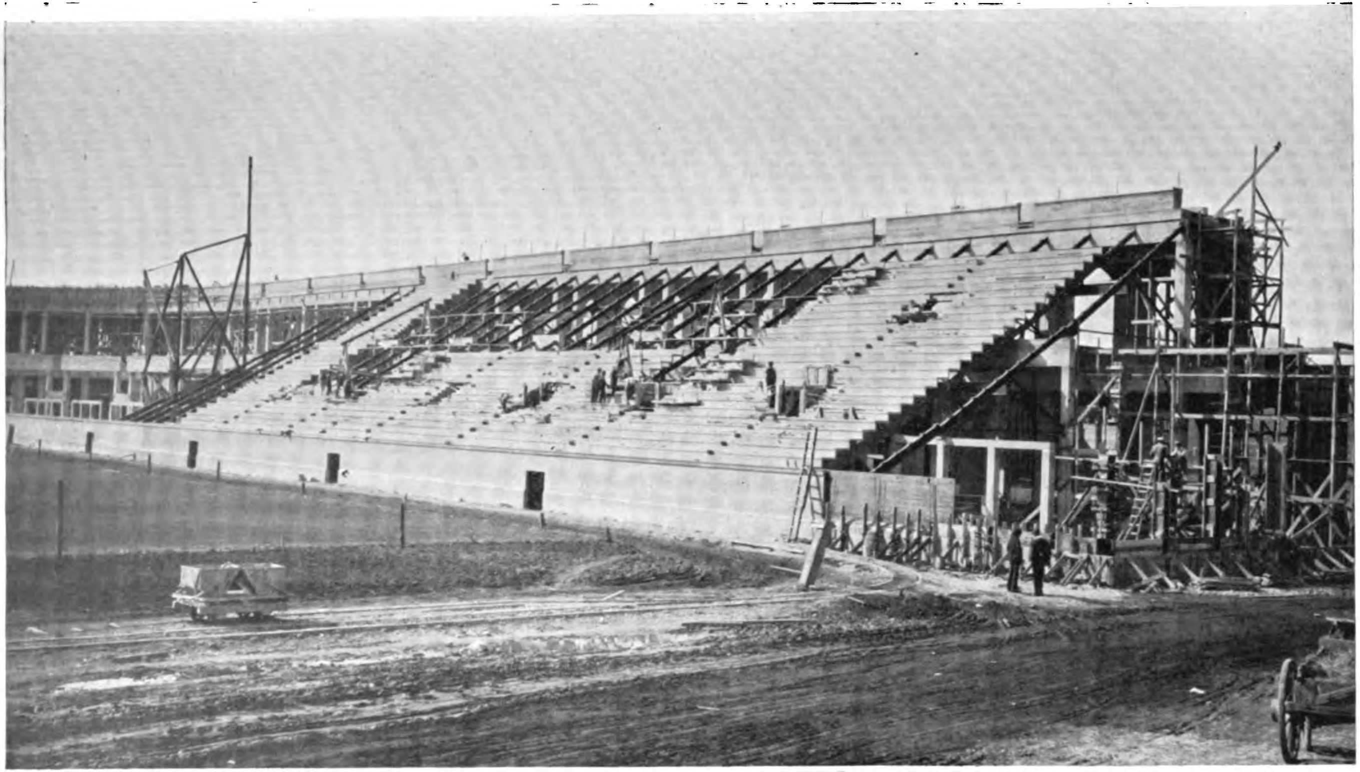


FIG. 3.— WEST WING UNDER CONSTRUCTION.

may be heightened by various devices, such as twisting, in the case of a square rod, so that each of the four edges forms a spiral, or providing transverse ridges upon the surface of the rod. Concrete thus reinforced is designated by many names, among which are steel-concrete, reinforced concrete, and ferro-concrete. It proves a suitable material even in very light and thin sections for floors, beams, columns, girders, walls, chimneys, tanks, standpipes, bridges, and for almost any permanent structures which have hitherto been made of wood, stone, brick, or steel.

Its advantages lie in its low first cost, durability, non-inflammability, speed of construction, wide-spread source of supply for all the materials, and applicability to almost all forms of structures. It combines many of the good points of common masonry and of steel construction, and is free from some of the important disadvantages of both. The design from an engineering point of view is by no means a simple problem.

Of course like other construction work, constant and close inspection is necessary, — to see that the materials are properly selected, that the concrete is correctly proportioned and mixed, and that the steel is put in and in the proper places.

The cost per cubic yard is not specially low as compared with stone or brick, but its economy lies in the *very thin sections* possible and satisfactory — the end walls of the Stadium, for example, being in the main only four inches thick, stiffened at intervals by vertical concrete ribs.

The concrete itself may, with suitable choice of the stone, be of a very pleasing color. Its appearance depends upon the treatment of the surface. It is apt to be unsightly, both in color and texture, when the moulds are taken off and how it is best to remedy this is still a matter of study. Picking, washing, brushing, possibly sand-blasting, may be used to get down to the body of the concrete.

Steel as a reinforcing metal combines the advantage of having a high degree of tensile strength and almost exactly the same rate of expansion and contraction from temperature changes as concrete — therefore no breaking of the bond between the steel

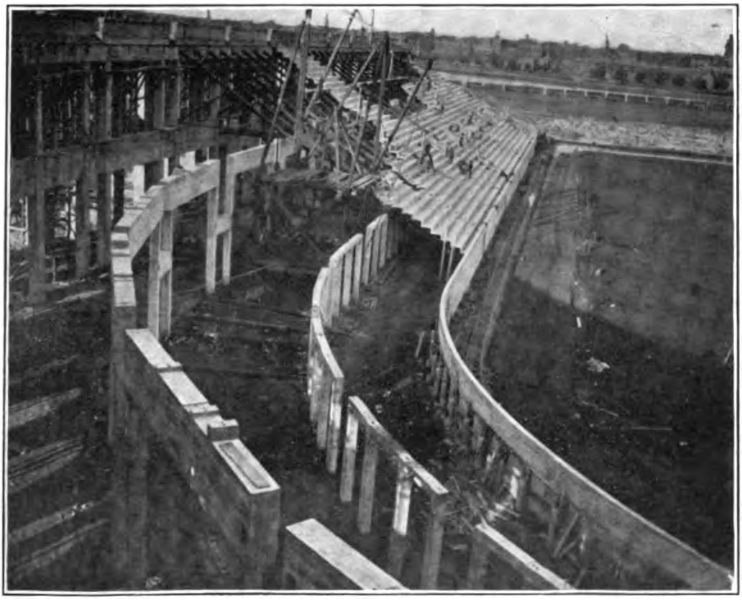


FIG. 4.— PORTION OF CURVE AND WEST WING UNDER CONSTRUCTION.

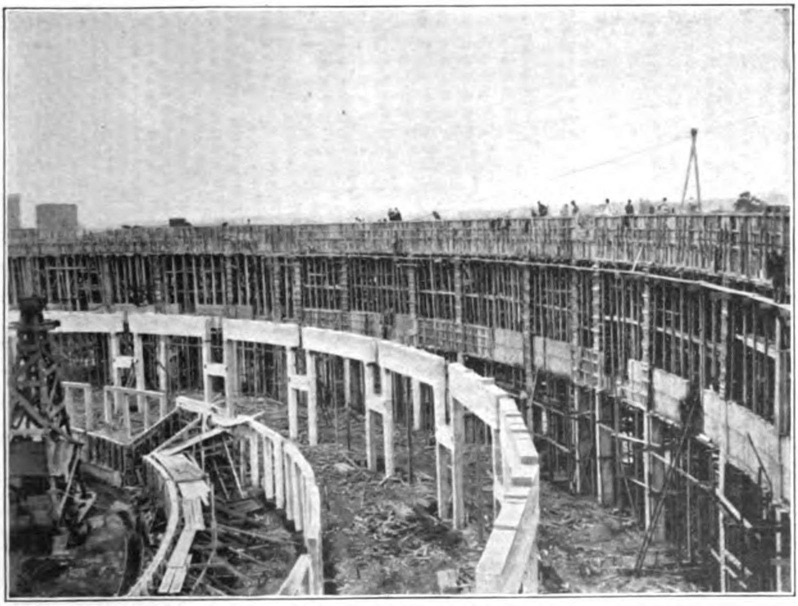


FIG. 5 — CENTRAL PORTION OF CURVE UNDER CONSTRUCTION.

and the concrete need be feared from this source. Fortunately, also, the concrete in which the steel is bedded protects the steel entirely from rust.

In the Stadium will be found examples of steel-concrete foundations, columns, girders, stairs, floors, walls, parapets, etc. It might have been made entirely of steel-concrete, but the expense would doubtless have been greater and the length of time required for construction very greatly increased.

Ever since the erection of the small steel grandstands in 1897 — the ones now used on the baseball field — the feasibility of erecting similar but much larger ones has been a subject of study. It was seen that the large amount of steel work exposed to the weather would be a constant source of expense for painting and moreover, its appearance could hardly be made acceptable. The only satisfactory *seating surface* for such a structure from the point of view of fireproofing and permanence was obviously some form of steel-concrete. So much of the structure having to be concrete anyway, it was decided to go further and use steel-concrete for the great bulk of the work,— using steel beams and trusses only where they would be under cover and invisible from the exterior.

The Stadium is, accordingly, a steel-concrete and steel grandstand, U-shaped in plan, affording seats for some 23,000 spectators. It consists essentially of five parallel rows of steel-concrete girders, columns and piers, with their foundations, extending around the U from tip to tip, and supporting a system of steel beams and trusses crossing them transversely (Figs. 1–5 and Pl. 1), which in turn support lines of steel-concrete slabs running around the U and forming the seating surface. The rows of steel-concrete work are designated by the letters A, B, C, D and E, counting from the interior outward. Fig. 5 shows the four inside rows on the curve, rows A and D not yet stripped. Row A, besides supporting ends of steel beams, includes the front parapet, a wall about eight feet in height and continuous around the U. Rows B and C support only steel work; row D supports the outer ends of the steel work and shares with row E the support of two steel-concrete

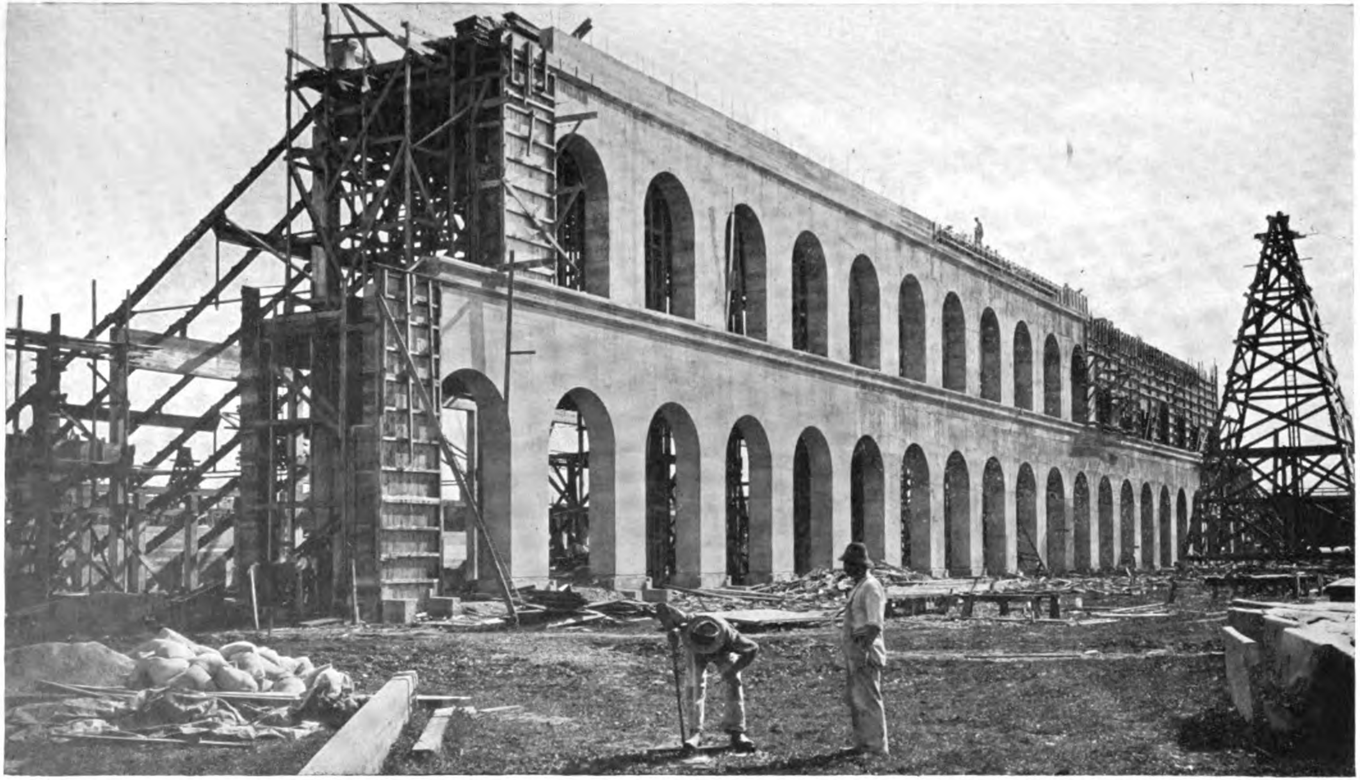


FIG. 6.—POSITION OF WESTERN FAÇADE (ROW E) SOON AFTER REMOVAL OF FORMS.

promenades or galleries about twenty feet in width at levels of 25 and 50 feet above the ground and running from tip to tip of the Stadium. Row E (Fig. 6 and Pl. Vb) is a line of hollow piers separated by two stories of arched openings, and to carry a wall at the third story which will support the outer edge of the roof of the upper promenade, whose inner edge is to rest on a colonnade supported by row D (Pl. I). The openings of the lower of the two arcades of row E afford access to the stairways to the seating surface, and the openings of the upper arcade afford outlooks from the promenade behind them.

The steel-concrete work includes, besides all the columns, piers, main girders, floors and the seating surface above mentioned, the outside and end walls, staircases and all parapets and railings. The foundations are all of concrete, some reinforced, some plain. All parts exposed directly to the weather are of steel-concrete.

The developed length of the U at the outside row is 1390 feet, and the uniform width across from front to back of the wings of the U is 95 feet. The area actually under cover is some 120,000 square feet, about 40 per cent. of which is devoted to the semicircular end, and the rest to the two straight wings. The lowest seat is about 7 feet and the highest about 50 feet above finished grade. The number of rows of seats is 31.

The over-all length of the Stadium is 576 feet, and the width is 420 feet, both exclusive of some small towers to stand at each tip of the U and a flight of two or three steps to extend the whole length of the outside. The highest part of the structure now finished is about 53 feet above the ground, but the addition of the covering for the upper promenade will make the final height 72 feet.

Most of the concrete work was cast in place in wooden forms in the ordinary way, but the slabs of which the seating surface is composed were of a special mixture and were cast in sand molds upon the ground in units weighing about 1200 pounds each, and after hardening were hoisted into place and set upon the supports which were meanwhile being prepared for them. The

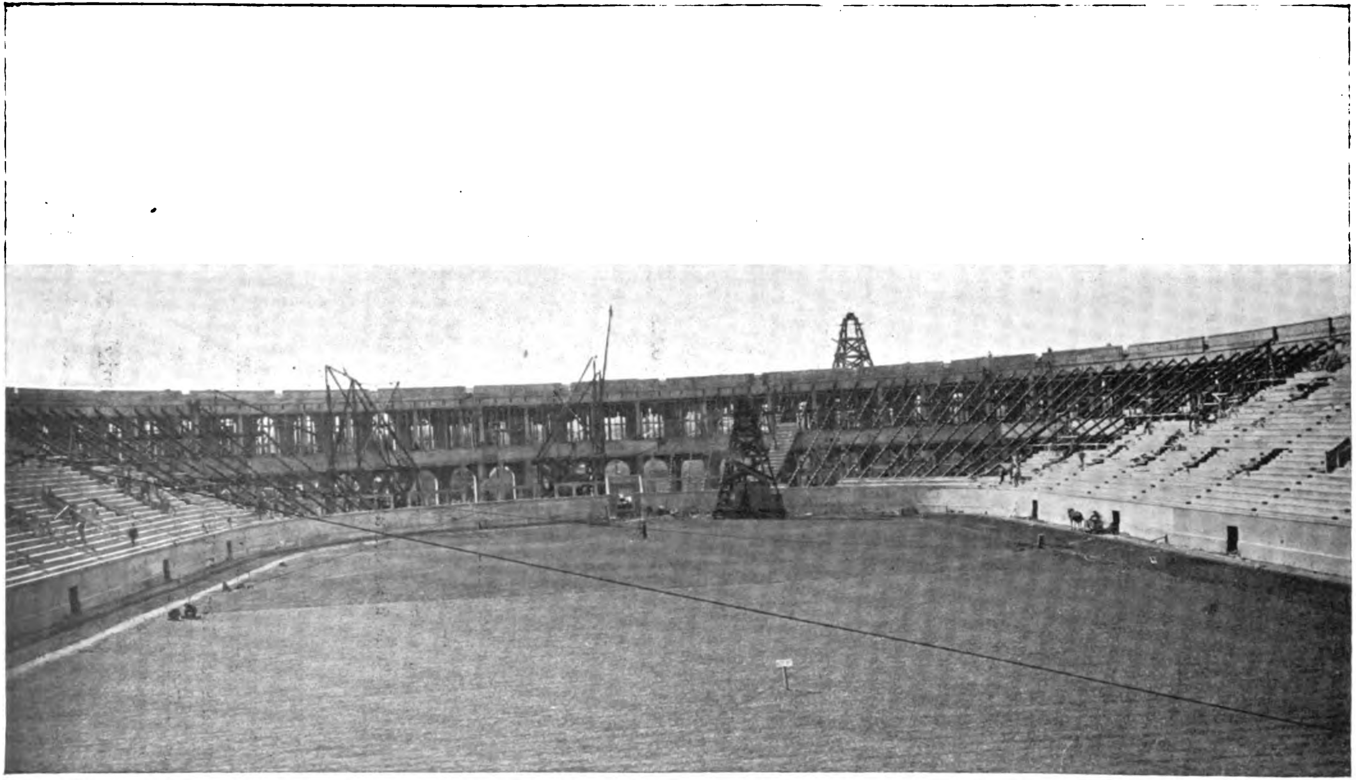


FIG. 7.—GENERAL VIEW OF CONSTRUCTION OF STADIUM.—WORK PROCEEDING FROM THE TWO WINGS TOWARDS THE CURVE.

concrete cast in the wooden forms is to be picked so as to remove the board marks, while the seat slabs have a satisfactory surface given by the sand mold. The steel reinforcement in all the concrete consisted of Ransome cold-twisted square steel bars (ranging in size from quarter-inch to inch), supplemented in the seat slabs with a special wire netting with rectangular meshes, electrically welded at the joints.

Three grand divisions of the work went on simultaneously — the casting of the standing concrete (work going on on both wings at once), the manufacture of the structural steel work and of the concrete slabs. The results of these three operations were assembled by the setting of the steel work and the slabs. Fig. 7 shows the setting of the structural steel and the seat-slabs closely following the completion of the rows of standing concrete.

The foundations are of the simplest character, as borings showed only hard gravel and clay to a depth of at least 40 feet. They are mere concrete or steel-concrete blocks laid on the natural ground just below frost so proportioned as to keep the maximum pressure on the ground from exceeding 7000 pounds per square foot.

The methods and principles followed in the design of the remainder of the concrete work may conveniently be taken up under three general heads, viz.:

(1) Columns.
(2) Girders.
(3) Walls and parapets.

Columns.

Although all the columns contain twisted rods in the form of verticals at the corners, with or without horizontal hoops at close intervals, this steel was not counted on as furnishing compressive resistance. Its utility was conceived to lie in withstanding any slight flexure that might come upon the columns from lateral forces due to temperature changes or other causes. This reinforcement consisted of three-eighths and half-inch rods,

depending on the size of the column, one such rod being placed near each corner of the column. In order to guard against the risk of such slender rods buckling when too near the surface, square hoops of quarter-inch rods encompass them in horizontal planes at intervals, keeping their free or unsupported lengths within reasonable limits. See Pl. II–IV.

Beyond the rôle thus assigned to the steel in the columns, it seems highly probable that, in the case of a severe overload, this steel would furnish a considerable element of protection against the failure by shearing on planes of about 55 degrees to the horizon characteristic of prisms of materials like plain concrete.

The columns proper range in size from 14 × 14 inches to 24 × 33 inches. Besides these, and designed in the same general way, with corner vertical rods and horizontal hoops, except that they are hollow, are the piers showing in the outside wall and already mentioned, which are externally 66 × 36 inches, the walls along the 66-inch side being 4 inches thick and the other two 6 to 8 inches thick, the 8 and 6-inch ends being counted on as furnishing the whole compressive strength.

The cross-sections of the columns were determined by applying an allowable compressive stress of 350 to 400 pounds per square inch to the maximum combined live and dead load, increasing the results thus obtained whenever necessary to keep the ratio of the length to least side of column down to about twelve, or to give round numbers for dimensions of the section. The structural steel work and concrete girders and struts were arranged to aid in keeping down the ratio of length to least side

Girders.

The sizes of the girders were determined by the use of principles worked out in France and confirmed in this country. The sizes chosen are somewhat larger than would be taken by some practitioners, but the matter was realized to be one on which engineering science had not yet reached a final position and of the two a conservative policy was the one to be preferred.

The steel reinforcement in the girders consisted of horizontal rods running the whole length of the girders and close to their lower face. In addition to this there was a system of reinforcement composed of series of smaller rods in a vertical position spaced at intervals along the girder to prevent cracks beginning at the lower face and running diagonally upward toward the center of the span. These rods were bent so as to pass entirely under the horizontal rods and their upper ends were hooked as a special precaution against slipping through the concrete.

The relation between the amount of steel in the horizontal system to the whole cross-section of the girder is of much importance. The larger the percentage of steel in the girder the lower will fall the neutral axis, or in other words the larger the portion of the girder section made effective to resist compression. A girder may be designed so as to fail either by the rupture of the steel rods on the underside or by crushing the concrete on the upper side, or by diagonal cracking. The first arises, of course, from a low percentage of steel, and the resulting failure is complete and comparatively sudden. With steel enough present so that the concrete will fail first the failure is far more gradual, and it may happen that a girder badly shattered may still be capable of carrying a large load. The abuse which a concrete girder with a fair proportion of steel will stand, and the warning which it will give before utter collapse and dropping its load, is one of the properties of steel-concrete not always realized. Fig. 8 shows a slab similar in design to the seat slabs, but with the concrete entirely severed through the tread and up the riser, carrying as many men as could conveniently stand on it by virtue of the steel reinforcement alone.

The writer is inclined to avoid low steel percentages for the additional reason that they are generally uneconomical. Nevertheless circumstances may arise where sizes of beams or slabs acting as beams may be determined by considerations of rigidity or of provision against abrasion. In such cases a low percentage of steel may properly be used, always with the understanding that the safe load is then to be based on the comparatively low strength of the steel.

The girders in the Stadium ranged in size from 16 × 47 in. to 24 × 60 in. (Pl. I–IV). They were of course usually straight, but in row D on the curve all the girders were made to conform to the semicircle. The objectionable effect of this curvature on the stability was partly counteracted by giving the girders in this part of the work overhanging ends carrying in the intervening spaces suspended spans. This made a series of cantilever girders (Pl. III, IV). An additional advantage of this cantilever system was that it distributed the loads so as to make it possible to keep the girders in Row D of the same size on the

FIG. 8. — STEEL-CONCRETE SLAB BADLY DAMAGED BUT STILL CARRYING HEAVY LOAD.

curve as on the straight wings, in spite of the fact that the spans were greater. This is believed to be a matter of much importance from the point of view of good appearance.

The ends of cantilevers and of suspended spans being critical points subject to very severe shear, were stepped so as to reduce the effective concrete area as little as possible and armored with special care. The stirrups used here were of special construction, placed in an inclined position, and were designed to resist the whole shear without aid from the concrete.

The cantilever ends tend to act as joints, at which the shrinkage stresses are relieved. The first suspended span to be built shortened in hardening and slipped on the treads of one of the stepped ends so as to show a crack throughout the extent of the risers of the joint, and in slipping spalled the corners of the step slightly. After this four 1-inch rods were put in at mid-height of the girder and lengthwise with it, crossing the joint and extending into both the cantilever end and suspended span far enough to develop the strength of the rods with a view to prevent this slipping, and, so far as seen, the result has been a success. Shrinkage joints are thus kept about 115 feet apart in this line. At the ends of these intervals are opportunities for shrinkage to take place harmlessly. Besides using the rods, the steps were finished off with a troweled surface truly level, so as to leave things in shape for a harmless slip should the rods prove ineffective. It was at one time planned to use two quarter-inch steel plates lubricated with graphite at each of these treads to facilitate sliding and to prevent spalling, but it did not finally seem necessary to go to such a length.

These lines of cantilever girders were subject to a very complex set of loads and were much cut up by promenade floor beams and passageways for stairs, so that they were the most troublesome of the girders to detail. The girders in row C, on the curve (Pl. II), were all straight — a series of chords — but support the ends of trusses and are hence much larger than the girders of the same row on the tangent, their section being 22 × 60 as against 16 × 47.

The promenade floors were made of slabs of inverted trough section about 8 feet 3 inches wide and some 20 feet in span, cast alternately in place, thus providing shrinkage joints at the edge of every slab; the thickness of the body of the slab is $4\frac{1}{2}$ inches, exclusive of the granolithic finish, and the flanges are 6 × 18, making practically a $4\frac{1}{2}$-inch flat floor resting on 12 × 18 joists 8 feet 3 inches on centers and 20 feet in span.

The seat slabs are a series of ____|'s set up so as to form a series of treads and risers (Fig. 9) and are to be classified as part of the girder work. They are of crusher dust concrete poured

at a consistency of cream reinforced by a half-inch rod at the base of each riser and electrically welded steel wire netting with rectangular mesh furnishing straight wires 0.162 inches in diameter, 5 inches on centers running across the treads and up the risers. The wires running the other way are somewhat smaller and closer together. In the treads this netting furnishes the ordinary tensile reinforcement for the span from riser to riser, besides hanging one edge of the tread to the base of the riser, and in the risers it furnished vertical reinforcement, for the

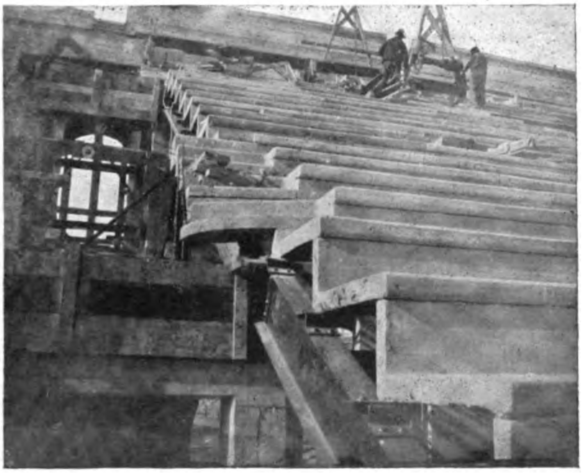


FIG. 9.— DETAILS OF SEAT SLABS AND THEIR SUPPORTS.

risers constituted a series of joists running from one steel beam to the next, the span being usually 8 feet 3 inches.

These slabs were cast in small units of about eight cubic feet each to facilitate handling and to provide amply against shrinkage cracks. They were some 4800 in number, and, including those on the curves, required ninety-five different patterns, counting rights and lefts as alike, and in many cases counting as alike such patterns as varied only slightly in length. On the semicircle they were made curved, but a constant radius was used for all, regardless of their distance from the center. The true radii would have had thirty-one different values, ranging

from 115 to 189 feet, but 166 feet 8 inches (1000/6) was chosen as a convenient mean to use for them all.

The handling which all these slabs underwent in storing and placing formed an automatic system of testing which was considered a distinct advantage of the method of manufacture. They were cast with one-eighth-inch allowance for end joints, but the sand casting proving to be a less accurate process than was expected, more or less picking and clipping had to be resorted to in setting them. An additional and probably more important cause for such modifications was inaccuracy in the setting of the structural steel.

The treads of these slabs are an example of concrete reinforced with a small percentage of steel and accordingly rated for strength from the point of view of the steel. This strength is ample almost to excess, even with this small allowance of steel, yet thinner sections of concrete were not seriously considered, three and a quarter inches on the average being adjudged a suitable minimum from the point of view of resistance to abrasion, shocks, etc., and the omission of the steel netting altogether was, of course, not seriously entertained — even though the concrete might, by counting on its tensile strength, be figured out as strong enough.

The design of these slabs was made in the light of tests of the behavior and strength of similar slabs in the laboratory of Pierce Hall. Later a number of the slabs actually made on Soldiers Field were tested to destruction. Fig. 10 shows one of these tests with a slab carrying 12,000 lbs. of cement in bags. This load caused a crack and was not carried farther, but a considerably higher load still would have been required to cause complete failure. Further tests of the slabs and of the efficacy of their setting was made by marching a body of twelve men over them after they were hoisted and set in place. These men were collected on one slab at a time and then caused to jump up and down as nearly in unison as possible. This put upon each slab about twice as many persons as could be seated upon it. The jumping was intended to bring to light what defects might appear from the boisterousness of the excited

crowds soon to occupy them. In this way several hundred slabs were tested in place and their behavior was entirely satisfactory.

Walls and Parapets.

The special problems in the design of walls and parapets which will be considered here is how best to provide for shrinking so as to minimize the evil of cracking from this cause or from temperature changes. One way is frankly to leave joints at short intervals free to open, using steel reinforcements between these joints to compel all the cracking effect to appear,

FIG. 10.—STANDARD SEAT SLABS CARRYING 12000 LBS. OF CEMENT.

if at all, at the joints so left. These joints are supposed to open in tolerably straight, clean cracks, and are not so unsightly as random cracks would be, but they are unsightly enough, especially as it is difficult to make the cracks turn out as

straight as expected. There is, therefore, a strong incentive to resort to the other method of treatment and attempt to defy the temperature and shrinkage changes by the aid of proper reinforcement with steel. M. Considère's experiments afford a rational basis for expecting success from such a venture, reinforced concrete having been shown by him to be capable of stretching to many times the extent of that of which plain concrete is capable without showing cracks. Moreover at least one case was on record in American practice confirming the practicability of the method.

In the outside wall of row E of the Stadium there was nothing else to do but to depend upon steel reinforcements to prevent shrinkage cracks. It was a place where cracks of any kind would be most unsightly. Expansion joints were left at intervals of 16½ feet, as in the front parapet, but they could hardly be placed elsewhere than over the center of the piers, in spite of its being realized that the friction from the weight of the superimposed mass would effectively prevent all sliding, and thus prevent such joints from being effective. The amount of shrinkage to be expected in setting, or cooling to the minimum temperature was estimated not to exceed about .0005 to .0006 of the length. To prevent this shrinkage was equivalent to stretching the concrete as the temperature fell, in order to keep its length constant. Investigators of this subject in France and in this country report that with a reinforcement of one per cent a stretch of .00078 or perhaps more may be endured without cracking. This seemed to offer sufficient margin and as the two faces of the wall in question were only 4 inches thick, one per cent reinforcement was quite feasible — only a half inch rod every six inches being required — and was adopted (Pl. Vb). Now after six to nine months' exposure, including one of the severest winters in many years, this wall shows only one crack, and that one hardly visible and not in any way threatening to the stability of the structure. The joints did not open at all, showing that the concrete between them must have actually stretched as expected.

The front parapet was executed upon the principle first men-

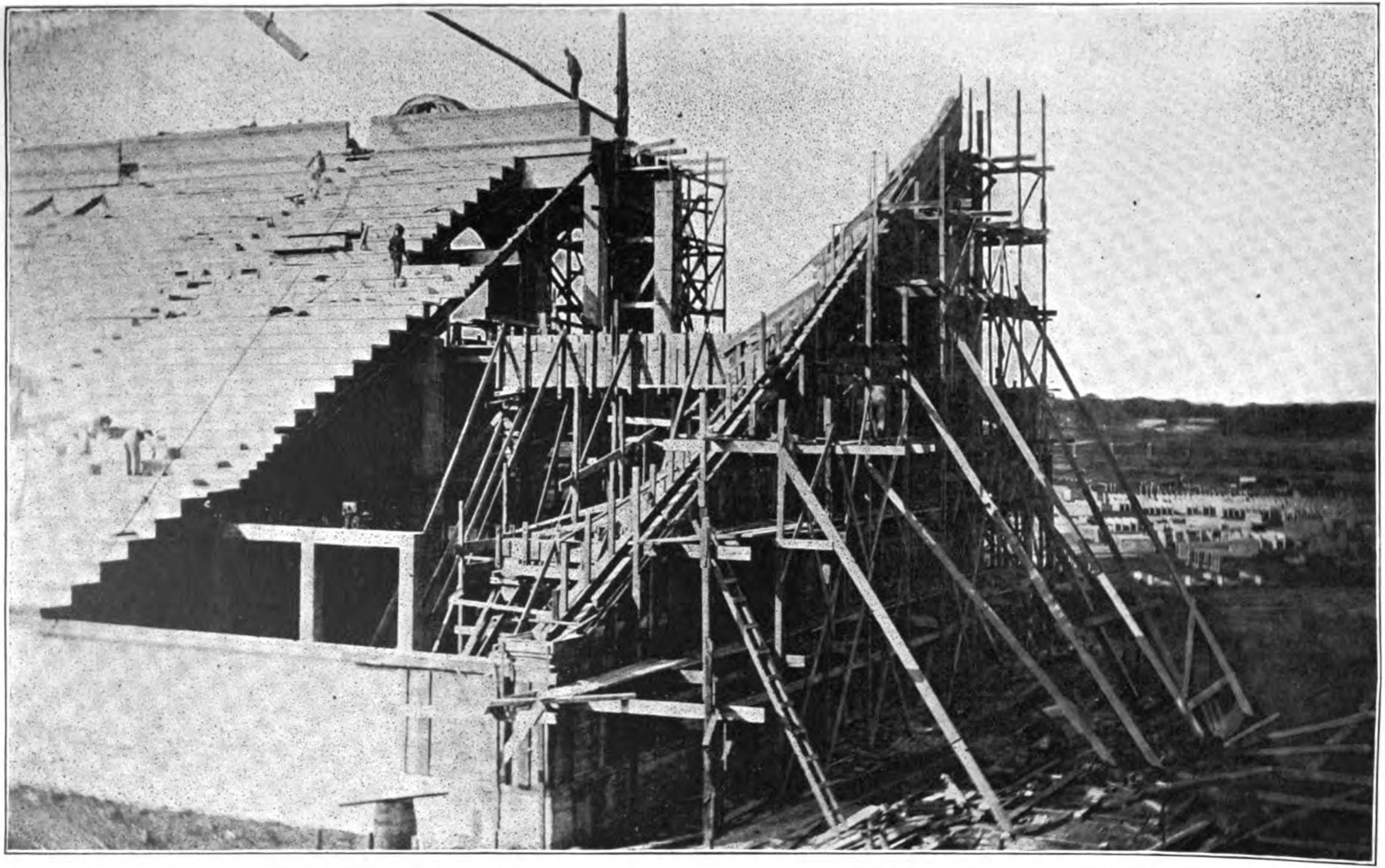
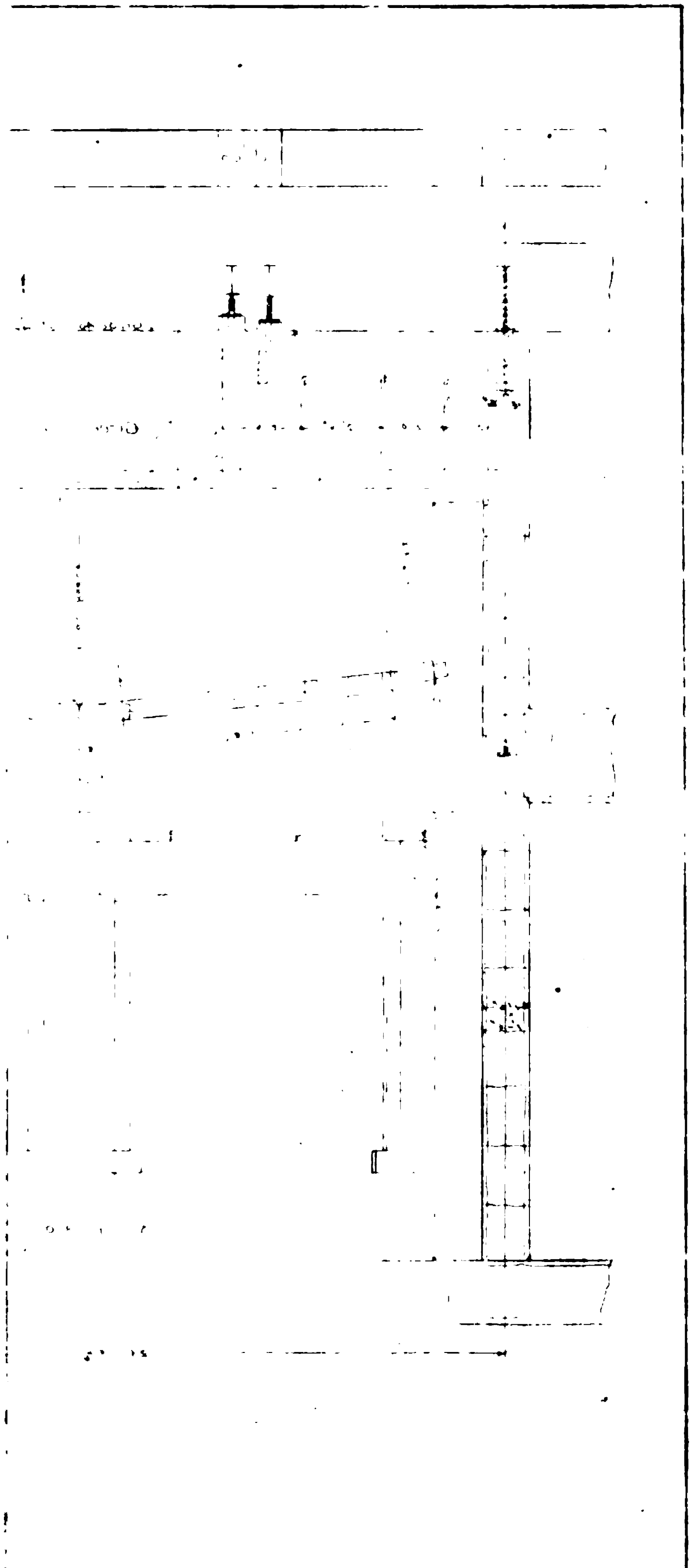


FIG. 11.— FORMS FOR END WALL OF WEST WING OF STADIUM.— IN THE MIDDLE DISTANCE SEAT SLABS READY FOR SETTING.

tioned, shrinkage joints being left every $16\frac{1}{2}$ feet, which opened perceptibly immediately upon the hardening of the concrete, and now constitute open joints sometimes a sixteenth of an inch in width, changing perceptibly as the temperature rises and falls.

The experience with the back wall being reassuring, and the tying together of row D into continuous sections of about 115 feet each causing no harm, it was determined to apply the same principle to the broad expanse of the end walls, which formed the finish at the tips of the U. These walls are some 75 feet long and from 9 to 50 feet high. They are in the main mere curtain walls only 4 inches thick, supported by a series of columns with which they are monolithic (Pl. Va). These walls are armored freely with quarter-inch rods — less care being taken to keep the percentage up to 1 per cent. than was observed in the back wall, the smaller area involved being regarded as justification for venturing below the 1 per cent. These walls have passed the winter's exposure without developing any cracks whatever on the exposed surface. Fig. 11 shows the forms for one of these end walls partly filled.

In closing the author begs to refer the reader interested in the more technical details of the girder design to the paper mentioned in the footnote at the beginning of this article.



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METHODS OF CONSTRUCTION OF THE HARVARD STADIUM.

BY HENRY H. FOX, INSPECTOR OF CONSTRUCTION.

THE dimensions of the Stadium and the rapidity of construction necessary to get the seats in place for the Harvard-Yale game of 1903, demanded extraordinary and extensive arrangements for handling materials. To some extent time was worth more than money. The ground was not broken for the foundations until after the Class Day game, and the structure could not even be fully staked out until after the baseball seats had been entirely removed. Work began on a few foundations near the ends on June 19, but the real work of erection was delayed until the early part of July. There were thus about four months and a half in which to bring the seats to a stage of construction sufficiently complete for use.

Concrete for the foundations was required while the rival merits of different plans for handling materials were still under discussion. Pending the decision of this important matter concrete was mixed by hand, and by a small spiral machine mixer, temporarily installed. The amount of concrete necessary to complete the Stadium was about 250,000 cubic feet, and the height to which it had to be hoisted varied from a few feet to seventy feet. In consequence, two inclined cable-ways (Fig. 1) were stretched from towers on each side of the work. The carpenters and riggers were started putting up these towers as soon as timber could be hauled to the Field. Tracks were laid, and when the cable-ways were ready for use a revolving drum called a Smith mixer was installed (Fig. 3). This drum was driven by a gasoline engine. The general arrangement of the plant is shown in Fig. 1.

A proper amount of cement, sand, and gravel for the concrete having been decided upon, the following method of measuring out the ingredients was adopted. Three bags of cement were carried out and placed upon a skip (this kept one man

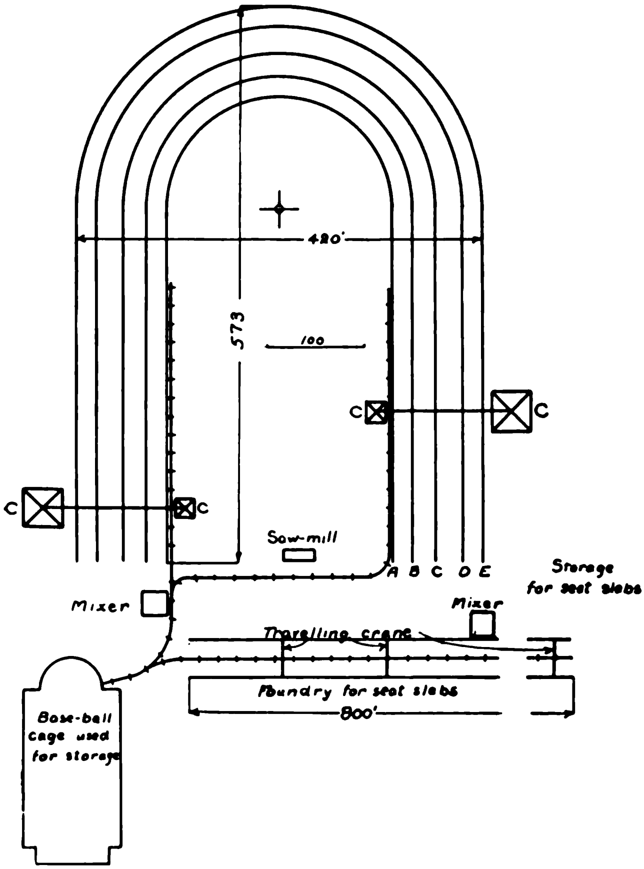


FIG. 1.—GENERAL PLAN OF CONSTRUCTION PLANT.

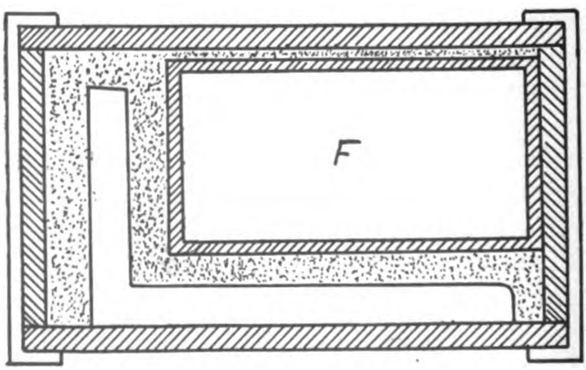


FIG. 2.—SECTION OF SEAT SLAB MOULD.

busy all the time); a bottomless box was used on the same skip to measure the required amount of sand. Since this box had previously been made of the right dimensions, no intelligence was required of the man who shoveled the sand into the box except to get it level full. A number of wheelbarrows of broken stone were then dumped on the skip after the removal of the box, and the whole was hoisted by machinery to the mixer. The proportions of the parts measured by the above method were supposed to be one part of cement to three parts of sand and six parts of broken stone, but as a rule the concrete was somewhat richer in cement than this would indicate.

From the mixer the charge of concrete was discharged into two buckets, each containing ten cubic feet. A record was kept of the charges. The buckets were hauled out on flat cars to points beneath the cable-ways where they could be hoisted to the various levels of the work. At first, some delay was caused in dumping the buckets by the fact that parts of the concrete stuck to the sides, and the buckets had to be scraped or pounded to get it off. This difficulty was entirely prevented by tying a piece of canvas to the side of the bucket and laying it inside before the charge was received from the mixer. Thus when the concrete came out, the canvas came with it.

In principle the process of moulding the concrete was similar to that of making castings of iron or of plaster of Paris, with the difference that boards were used to form the moulds. These boards, planed and well oiled, were set up and firmly supported in place at proper distances apart to form the thickness of the walls, beams, and columns (Fig. 4). The concrete was then poured into the hollows in the green or semi-liquid state and thoroughly tamped to remove all air spaces. Straight or curved steel rods were laid in the concrete at regular intervals to hold it together against tension stresses. These rods had been previously twisted to give them a firm hold within the material after it had hardened. The subsequent removal of the boards left the exposed surfaces somewhat rough and marked with the irregularities of the wood.

Work was begun at the open end, on both sides simultane-

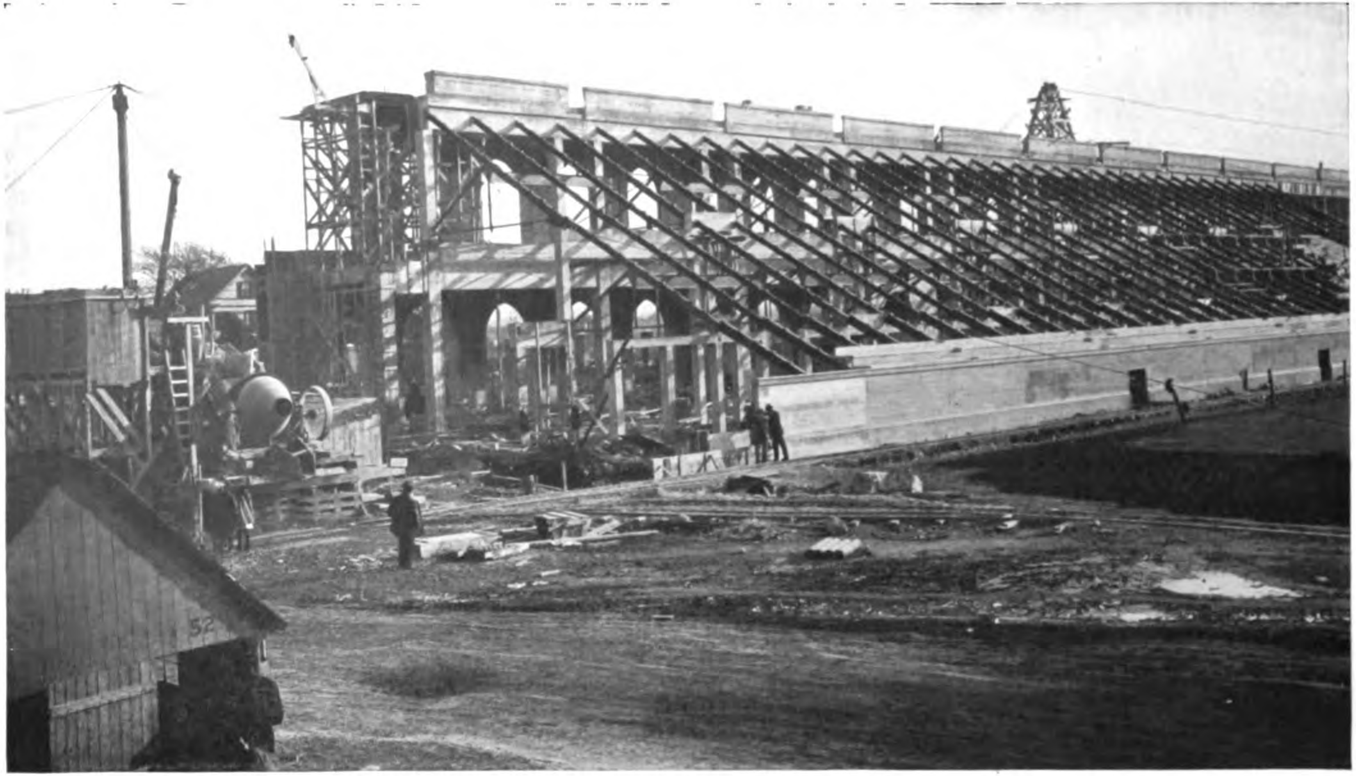


FIG. 3.— WEST WING UNDER CONSTRUCTION.— CONCRETE MIXER AT THE LEFT.

ously. The towers of the cable-ways were on tracks and were moved along toward the curve as the work progressed. The placing of concrete was concentrated as much as possible, to avoid wheeling in barrows; but so much time was required to complete a section of the two outside rows, from foundations to upper parapets, that the first story columns were often put in place while work on the upper floors was still several hundred feet behind.

The surfaces of all the concrete were thoroughly spaded. Mouldings were faced with mortar. During warm weather, granolithic finish for floors was laid on the same day as the main body of the floor, to insure a satisfactory bond. Later in the fall, when the cold weather delayed the setting, the finish was sometimes not applied until the following morning.

The necessity for speed had an effect also upon the cost of centering. The construction company hoped at first to be able to build the Stadium in sections about 100 feet long, and use the centering over and over again for each successive section; but since the centering in the first section erected could not be stripped before more was needed, new lumber was bought. The actual loss for this reason was, however, very slight, possibly nothing; for every stick of wood big enough for use was put into the temporary seats for the Yale game. Spruce boards one and one-half inches thick, planed on both sides and painted with crude oil on the side next the concrete, were used for all visible surfaces. Rough one-inch stock was used for cores. To facilitate repeated use of the same forms, they where built up in units or "panels," not too large to be easily handled. The forms were held together by bolts outside the forms whenever possible. In the case of large members, bolts ran through the concrete, and it was found very difficult to withdraw them after the concrete had hardened.

The first large girder which was filled settled about an inch in the middle during the filling. To offset any possible similar behavior on the part of the others, they were cambered about three-fourths of an inch; but since, in addition to this precaution, the temporary supports for the other girders were stiffened, the camber often appeared full size in the finished girder.

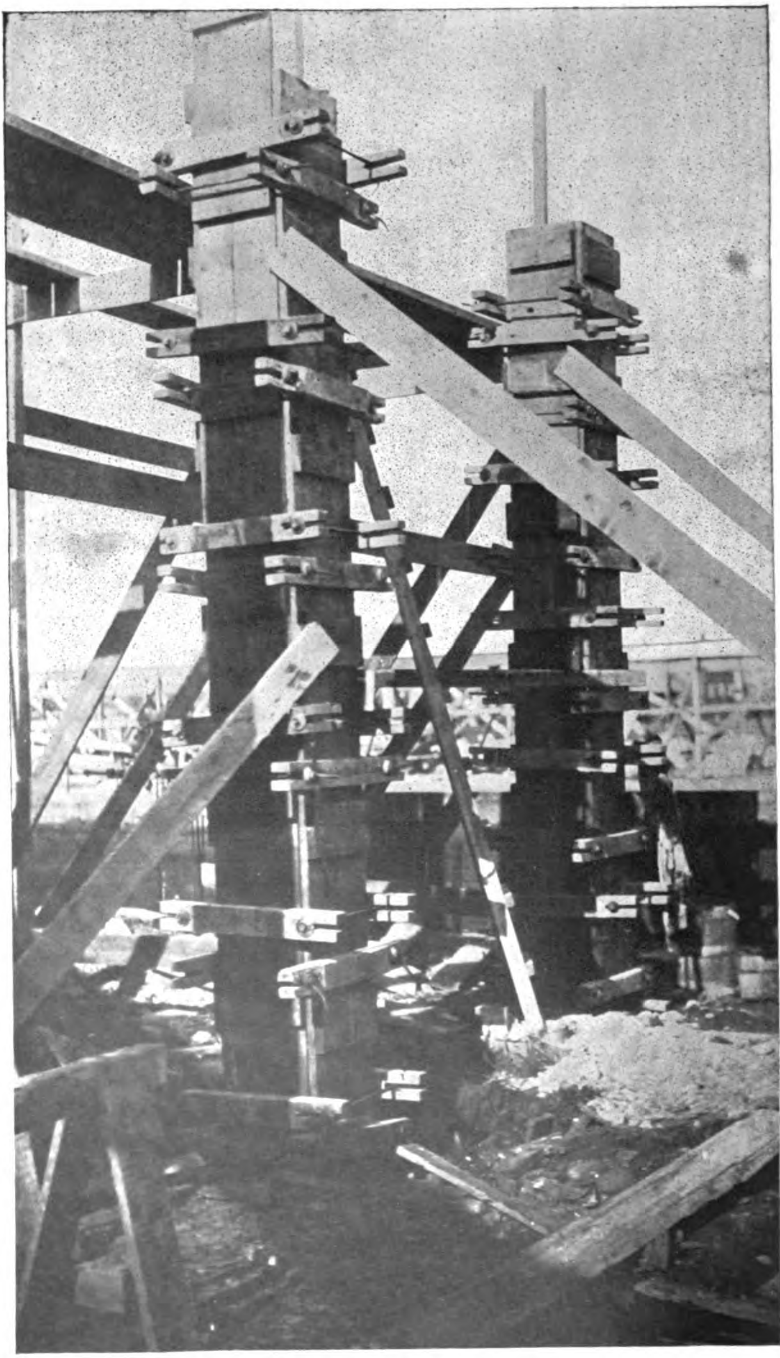


FIG. 4.—COLUMN FORMS IN PLACE.

Each side of the field had its own foreman. When the methods of the two foremen differed, a comparison was often instructive. For example, on both sides of the field the centering for the back wall on the lower story was used again for the upper story. This centering was built up in panels about six feet by twelve feet. One of the foremen, when ready to strip a section of the lower wall, one hundred feet long or more, drew the bolts, hitched a rope to one end of the section, and pulled it all down in a heap. The lumber was not damaged, but the different pieces were shaken apart, so that in order to make them ready for use again it was only necessary to draw the nails. Then the lumber was hoisted in small bundles with a block and tackle.

The other foreman thought he could improve upon this by hoisting a whole panel at a time from the lower to the upper story. For this purpose he ordered a breast derrick. The derrick did not come for three days, and when it did come, proved of very doubtful value; for it was a slow and difficult process to place accurately in position so large and heavy a panel; the derrick was in the way, especially when it was being moved (as it had to be for every panel); and the heavy strain in the guy ropes and in the footing of the derrick made slipping likely, and a consequent release of energy, which might be and in one case was destructive.

The steel rods, called reinforcement, were put in place by the concrete gangs, under the immediate supervision of an inspector. As a rule the rods slipped into place without much trouble; but sometimes, especially in the case of the big cantilever girders under the upper floor, some ingenuity was required to get all the reinforcement in position. The forms fairly bristled with steel. In the case of the columns, the hoops were not wired to the verticals before the concrete was placed, but were dropped over them at the proper intervals during the filling. The work of cutting and bending the rods and making them into frames or stirrups was done on the field. Six or eight men were employed at this when the demand was keenest. The rods were bent cold, except in the case of the above mentioned cantilever girders, in which some one inch bent rods were used. These could not be conveniently bent without heating.

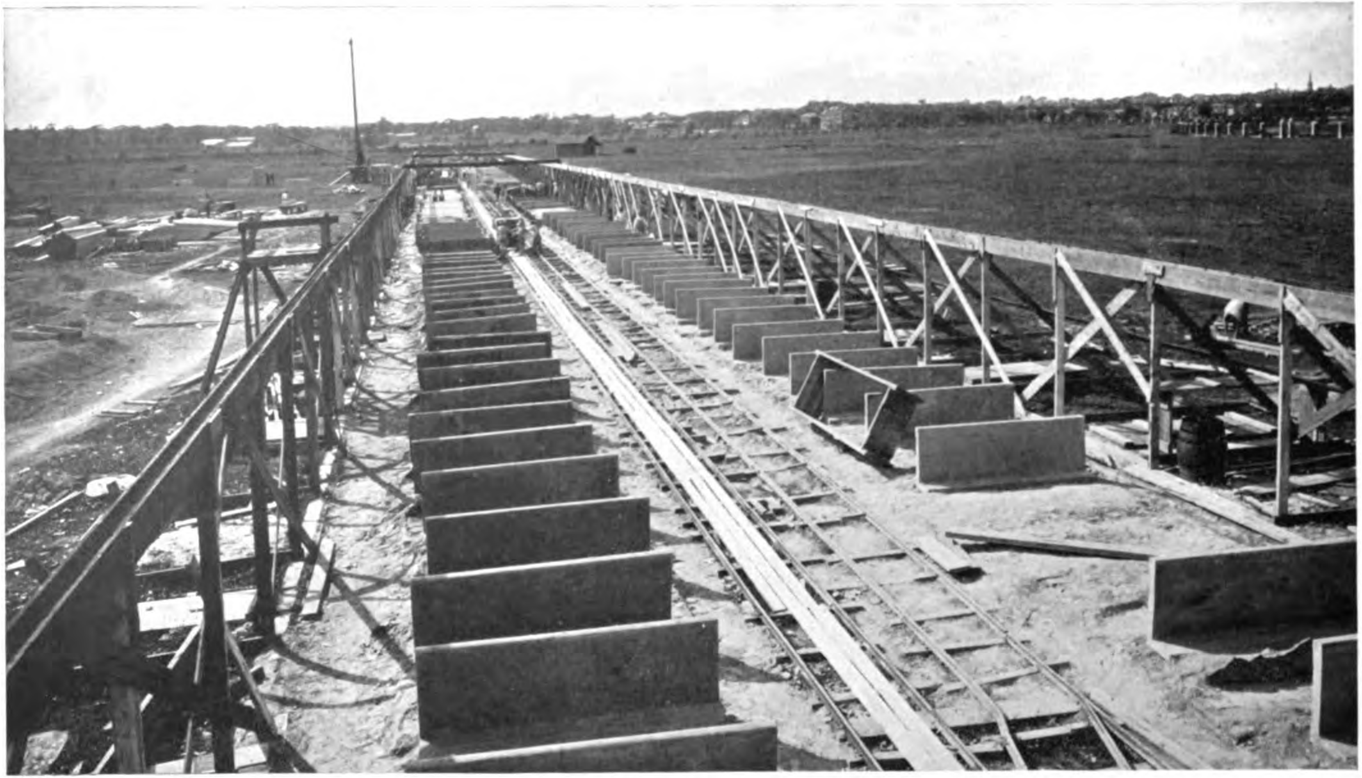


FIG. 5. — THE FOUNDRY FOR CASTING SEAT SLABS.

The casting of the seat slabs was begun early in July, and pushed forward with the greatest possible rapidity. The chances of having the 4500 slabs all cast in time seemed better than even, until the cold weather came and retarded the setting so much that the attempt was given up. Most of the slabs were of L shape, about 2 ft. 6 in. × 1 ft. 6 in. × 3 in. × 8 ft. 3 in. long. The patterns were packed in sand in a box, as shown in Fig. 2. F is a hollow box used as a filler to save sand. When the sand had been solidly packed, the cover was clamped on, the box was turned upside down with the aid of a traveling crane (Fig. 5), and the pattern was withdrawn (Fig. 7). The reinforcement, previously wired together, was then put carefully in place, guided by a templet which kept the wire mesh within one half inch of the surface, and the concrete, of the consistency of thick cream, was poured (Fig. 6). The mixing was at first done by hand at the end of the foundry. Later a small Smith mixer was set up about midway between the two ends. The foundry grew to a length of eight hundred feet; but even then the daily output rarely exceeded sixty slabs, the moulding was such a delicate operation. One gang of experienced moulders could turn out in a day fifteen moulds from the simplest patterns; but with the more complicated patterns four or five were often a day's work. In warm weather, the finished slabs were removed from the moulds in two or three days, and kept under wet burlap until they were needed.

The structural steel was put in place by a traveler which ran between rows B and C. The field connections were bolted. When the end of a beam or truss rested on the top of a column or girder, it was anchored with bolts set in hollow truncated cones of sheet metal which had been embedded in the concrete. Thick grout was poured in round the bolts. When, however, a column was continued above the seat of a truss, a pocket was cored out in the column and filled after the truss was in place. This method of construction is not to be recommended. It will be referred to again.

How to put the seat slabs in place was a puzzle. The "horse" shown in Fig. 8 was finally adopted, since its first cost

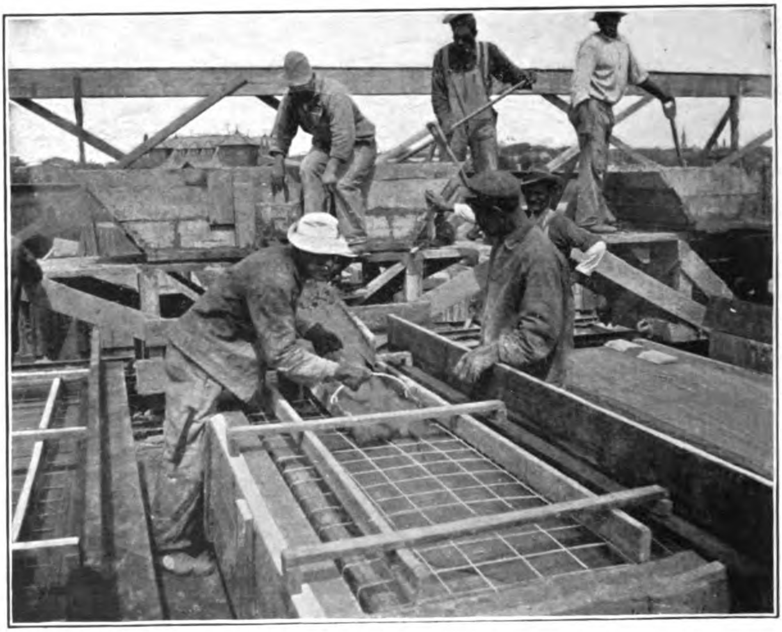


FIG. 6 — CASTING A SEAT SLAB.

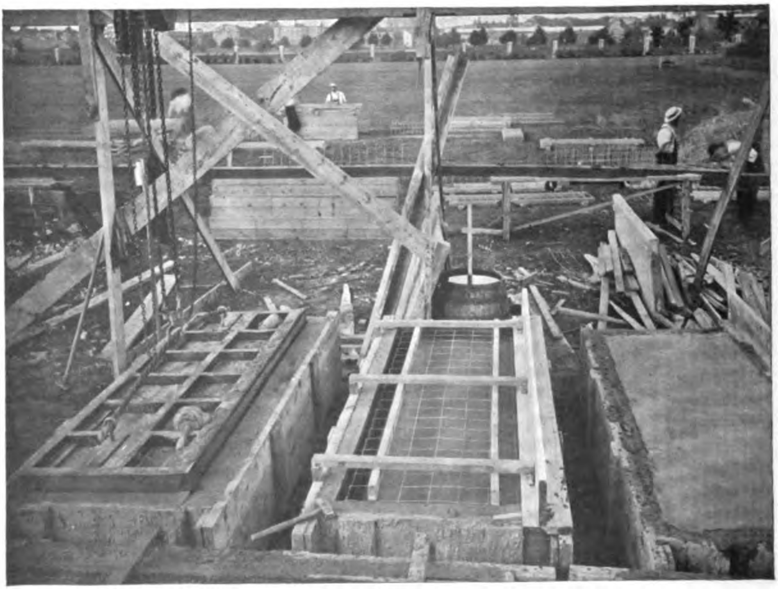


FIG. 7. -- SEAT SLAB MOULDS.

was less than that of the other mechanisms suggested; it was light and easily handled; and it could be quickly duplicated if the work did not progress rapidly enough. Setting seats by this means turned out to be a tedious process, especially on the upper rows. Fifteen seats were a day's work for one horse. To expedite matters, the cable-ways, the travelers for the structural steel, a boom derrick, two breast derricks, and a gin-pole were used at one time or another in addition to the four horses (Figs. 9 and 10). The slabs were hauled over the ground on wooden stone drags, the bottoms of which wore through quickly, though made of two inch oak plank. Four or five laborers were needed to load or unload a slab. The horizontal joints between slabs in place were filled with mortar made of a mixture of lime and cement. Some of the vertical joints also were filled in this way, but the greater part of them were left open.

Some points in the construction deserve special comment:

(1) It might have been more economical to run the cable-ways lengthwise of the structure, since much wheeling would thus have been avoided.

(2) Three gas engines were used, to run two mixers and a circular saw. Their habits were somewhat irregular, and the one on the large mixer showed an especial disinclination to begin work promptly in the morning; but as they did not require the constant attendance of an engineer, they were probably as economical as steam engines would have been.

(3) Considerable labor was expended, as has been mentioned, in withdrawing from the concrete the bolts which held together the centering. A recent number of one of the engineering periodicals states that this trouble may be prevented in an entirely satisfactory way by placing loose-fitting pasteboard tubes round the bolts.

(4) Board marks on the finished surfaces were easily removed by "picking" with a pneumatic toothed chisel. The cracks between boards, however, left marks which could not be entirely removed without picking off more of the surface than was desirable. This defect was probably due to leakage of water and cement through the cracks. To make a perfect sur-

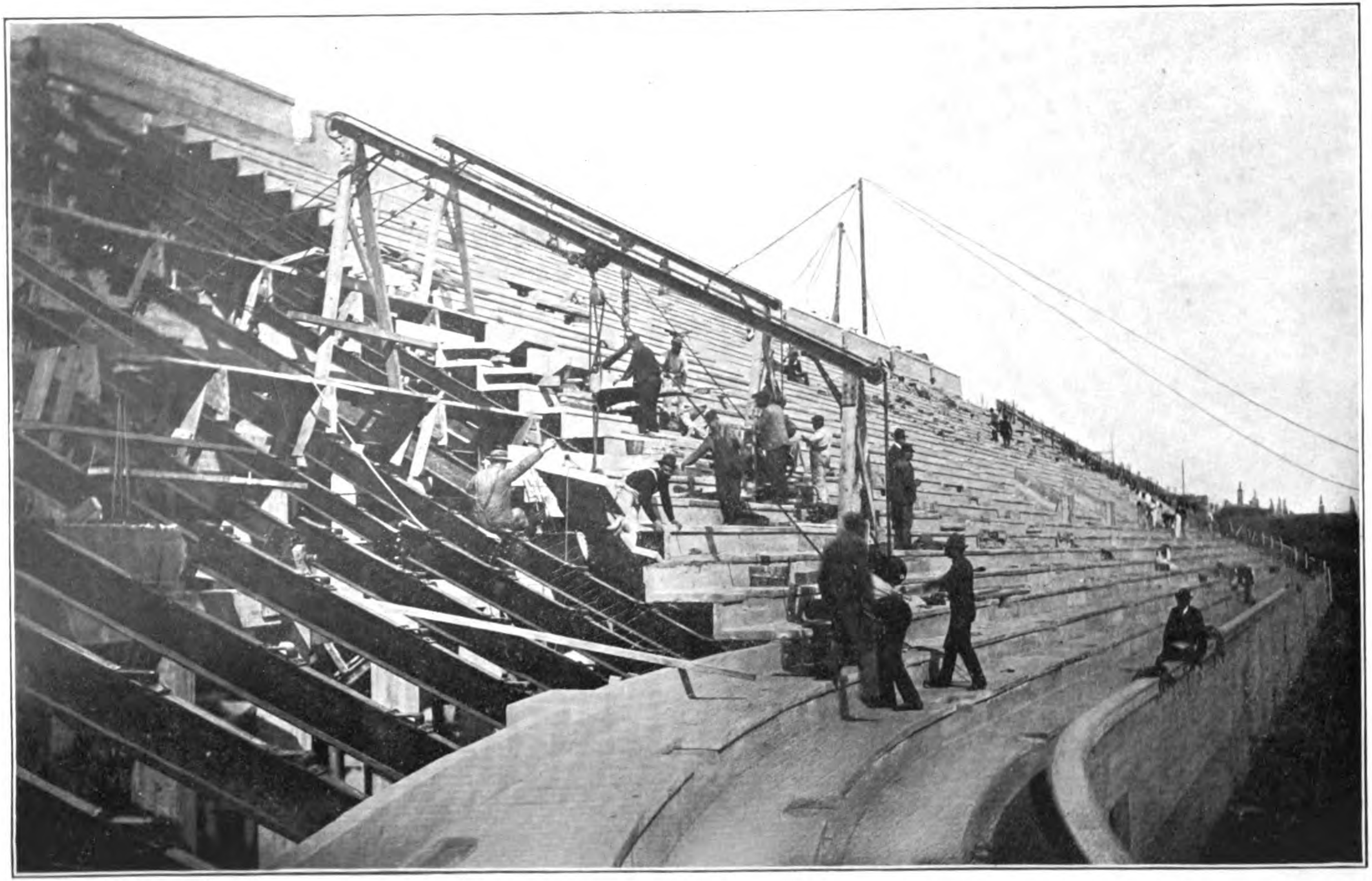


FIG. 8.— HORSES FOR SETTING SEAT SLABS.

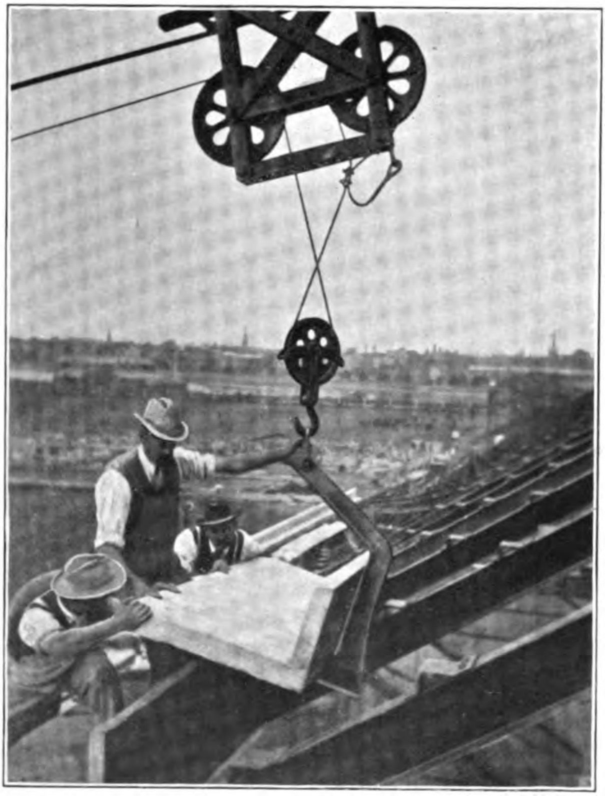


FIG. 9.—SETTING A STANDARD SEAT SLAB.

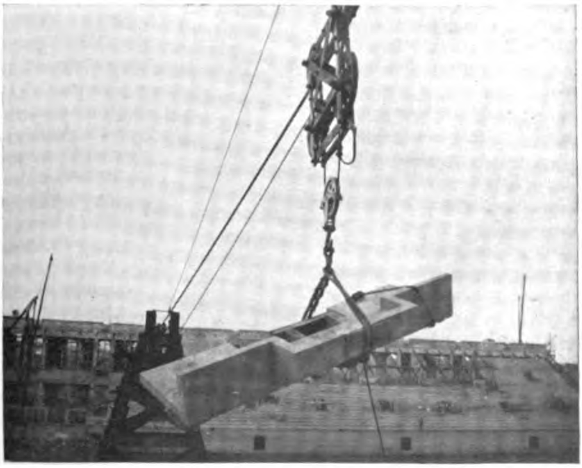


FIG. 10.—LOWERING AN AISLE SEAT SLAB INTO PLACE.

face some device should be used for insuring water-tight joints. The weakening effect of such leakage was well illustrated by the marked differences in firmness between filleted corners in columns and sharp corners. Sharp corners a week old could often be crumbled with the fingers; but the triangular fillet tightened the joint, diminished the leakage, and left a much superior quality of concrete.

(5) The practice of coring out from a column a pocket to receive the end of a truss is not commendable. In the first place, until the truss is in place, and the pocket filled with mortar, the column is weak at that spot. In the second place, unless the inspection is rigid, the pocket will never be entirely filled. The mortar leaks or shrinks away before setting, enough to leave a thin air space at the top. The resulting crack on the surface will then be carelessly plastered over, and the column though apparently sound will lack a considerable fraction of its supposed strength. At the Stadium these thin air spaces were filled by ramming in a comparatively dry mortar.

(6) Curious fine vertical cracks appeared on some of the columns after they were stripped. Although they seemed not to go deep, they caused some uneasiness until it was suggested that in all probability they were surface cracks caused by the swelling of the wood as it became soaked with water from the concrete, and the resulting stretching of the semi-solid concrete which adhered to the wood. This explanation was supported by the fact that every such crack ran along the middle of a board mark.

ANCIENT STADIA AND CIRCUSES.

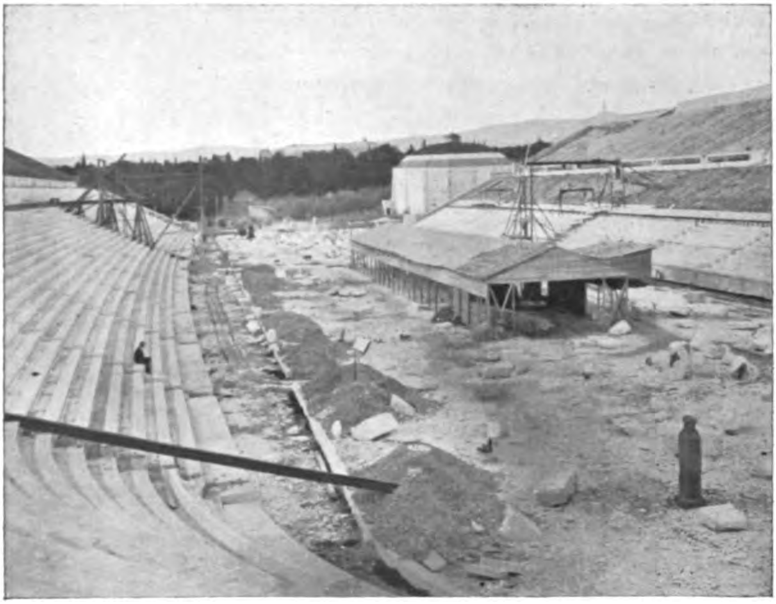
By H. Langford Warren, Professor of Architecture.

In view of the construction on Soldiers Field, of the so-called Stadium, it has been suggested that a brief account of the ancient structures which our football stand, in its general form, imitates, would be of some interest to readers of the '*Harvard Engineering Journal*.'

The stadium was a Greek measure of distance, equalling six hundred Greek feet, and as this was the usual distance for foot-races, the name came to be given to the structures where the foot-races and other athletic contests were held. The stadium at Athens is about 615 feet (English) in length exclusive of the terminal semi-circle, which was not included in the course. It approximated therefore quite closely our furlong.

Originally such contests took place in some convenient natural hollow and the spectators were seated on the ground on the sloping hillsides. Then the natural hollow was brought artificially into more regular shape and finally it was provided with seats, first of wood, as seems to have been the case at Olympia, and later of stone or marble, rising in steps, tier above tier, an arrangement similar to that in our Stadium, but laid directly on the sloping ground. The lower tier of seats was raised some three feet from the floor of the arena and some six feet in front of this a breast-wall formed a separation between the bank of seats and the arena, the space thus cut off serving as a passage to give access to the flights of steps leading to the seats. The floor of this passage was paved and below was a drain which served to keep the passage dry and to carry off the rain water that ran down from the tiers of seats. This was the arrangement at the stadium of Athens. The arena, the level of which was slightly above the surrounding passage, was similarly underdrained. There were separate underground entrances, leading directly to the arena, for the contestants and the judges. The ancient Greek stadia, as at Soldiers Field, were semicircular at one end and straight at the other.

As already stated, the Greek stadia were usually constructed where a natural hollow of the ground required but little shaping to bring it to the requisite form. This was the case at Athens. At Olympia, the stadium was, on one side, formed by artificial embankments of earth, while on the other, the natural slope of the hill was made use of. At Delphi, the seats rested on a masonry substructure; at Messene, they were partly supported



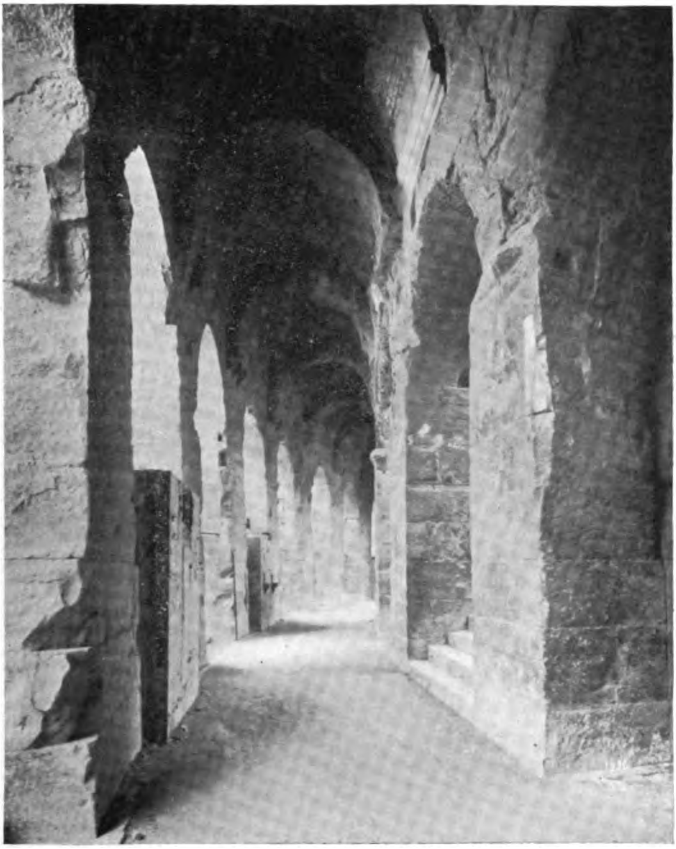
THE STADIUM AT ATHENS DURING RESTORATION.

by masonry and in part rested in the ground, and here there were colonnades in the form of a semicircle at the end.

The stadium at Athens does not date back to the great times of Pericles but seems to have been first constructed by the orator Lycurgus about the year B. C. 350. Herodes Atticus, the wealthy Roman, who did so much for Athens and for Greece, added seats of Pentelic marble about the middle of the second century of our era. The ancient structure had lost nearly all its marble work and had been largely buried but was

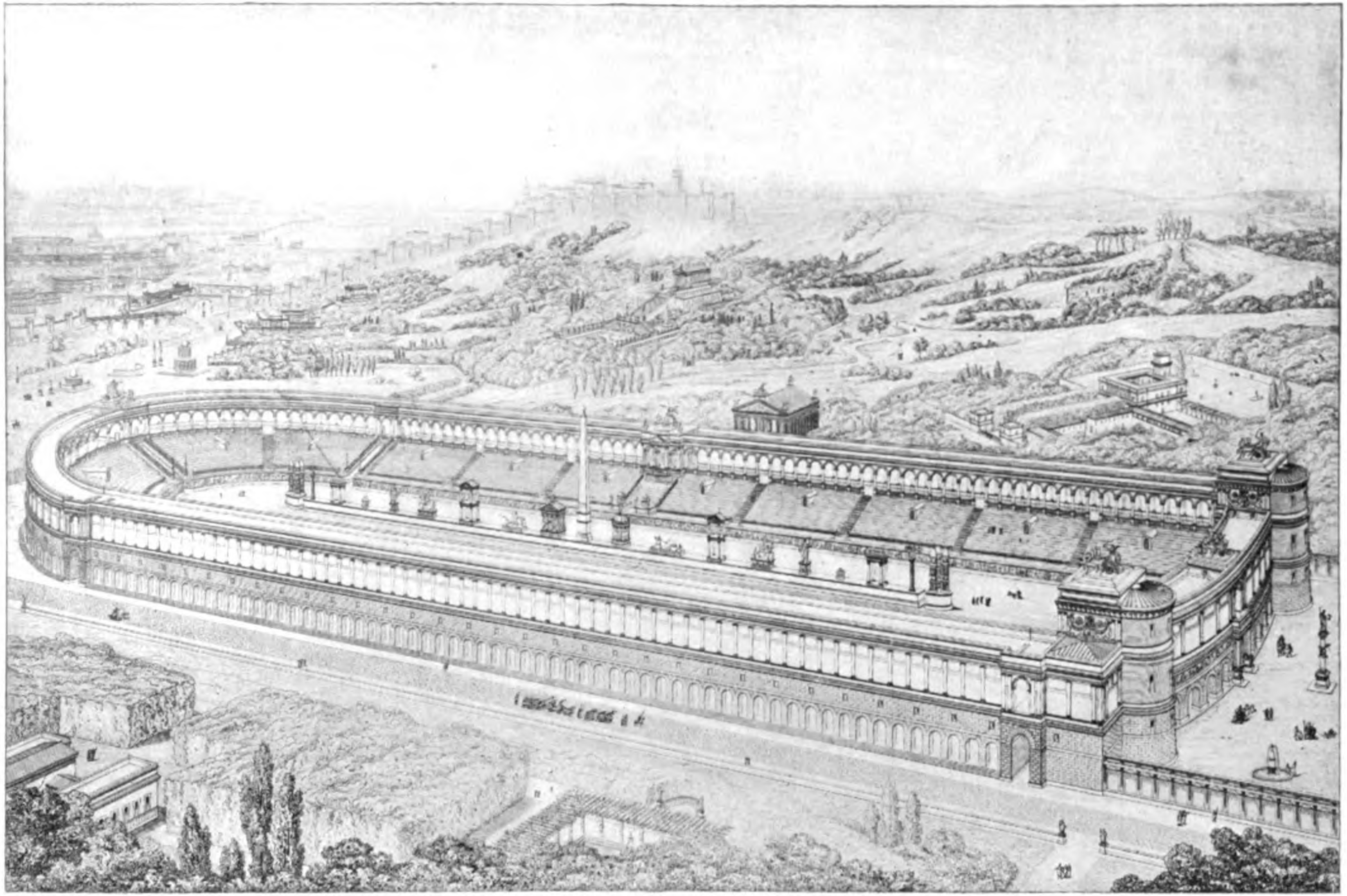
excavated at the expense of King George of Greece in 1869–70. It has now been completely restored as shown in the photograph here reproduced.

It may be interesting to compare the sizes of these ancient



VAULTS OF THE AMPHITHEATRE AT NIMES.

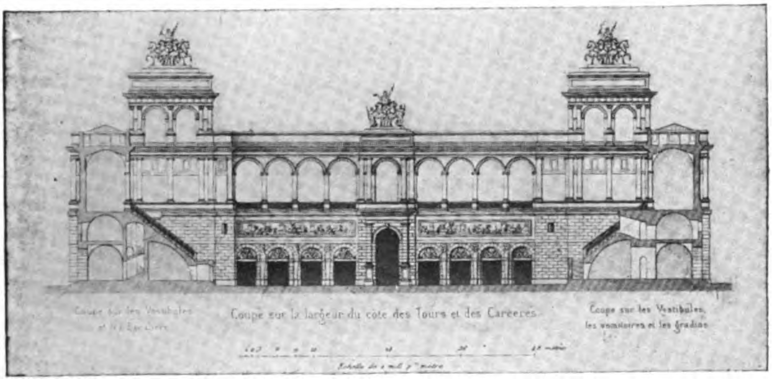
Greek structures with our modern one. The arena enclosed by the Stadium at Soldiers Field is 230 feet in width and 458 feet in length. Being intended for football primarily, it is relatively wide and short. The arena of the stadium at Athens is 109 feet wide and 669 feet long; that at Olympia is 105 feet wide and



RESTORED VIEW OF THE CIRCUS OF NERO AT ROME FROM LETAROUILLY'S 'VATICAN'.

692 feet long. The Stadium at Soldiers Field has a normal seating capacity of about 24,000; that at Athens will seat more than twice as many. Not all of the ancient stadia would seat as many spectators, for though the arenas were always of about the same size, some stadia had fewer tiers of seats. The stadium at Aizani in Asia Minor had an arena some 40 feet wider and 55 feet longer than that at Athens but it would seat only about one quarter as many people.

But as we have seen, these structures differed from our Stadium in that the seats were set directly on the ground. It remained for the Romans to build such structures on level sites



RESTORED SECTION OF THE CIRCUS OF NERO.

supporting the tiers of seats as it were on an artificial hillside of massive arches and vaults of solid masonry, utilizing the spaces below the seats for passages and staircases leading to the seats and, on the ground story, also for cages for wild animals. But these structures of the Romans, the circuses, were intended chiefly for chariot-racing, and were founded rather on the Greek hippodromes, which were in general similar to the stadia but were larger and wider in proportion to their length, being intended for horse and chariot racing. The development of stadium, hippodrome and circus was similar to that of Greek theatre, Roman theatre and amphitheatre, the latter group differing indeed from the former, mainly in plan, not in section or

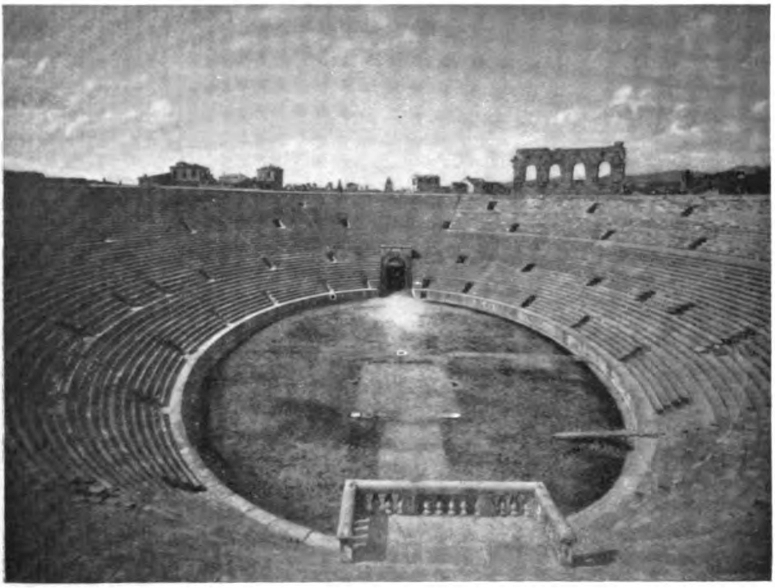
structure. The Colosseum in Rome is often referred to as the prototype of our Stadium, but the Colosseum is an amphitheatre, its plan being a complete ellipse. Our Stadium is rather like a small Roman circus, or like a Greek stadium of changed proportions, in which the general constructive scheme of the Roman circus is used, translated into terms of steel and concrete.

The Roman circuses were colossal structures in which audiences equalling the whole adult population of a considerable

EXTERIOR ARCADES OF THE AMPHITHEATRE AT NIMES.

city could be seated. The greatest of these, the Circus Maximus at Rome as finally enlarged would seat, it is said, 380,000 spectators. It was 705 feet wide and 2200 feet long. The Circus of Nero which stood on the site of the present cathedral of St. Peters, and of which we reproduce here a restoration, was about 350 feet wide and 1200 feet long. We need not here describe the detailed arrangement of its plan, with its great central wall or spina dividing the arena into halves so

that the chariots could drive up on one side and back on the other; what concerns us rather is the construction, the means by which the seats were supported. This was accomplished, as in the case of the theatres and amphitheatres, by means of a series of piers and vaults, whose massive and solid construction is one of the sources of impressiveness in these great structures. The exterior arcades of these wonderful buildings are simply the external expression of the vaulted structure



AMPHITHEATRE AT VERONA.

within. The arrangement may be illustrated by two views of the arena at Nîmes, in the south of France, one of the best preserved of the amphitheatres which dot the soil of the ancient Roman Empire. One of these photographs shows a portion of the exterior; the other is a view in one of the interior encircling corridors showing the vaulting.

At Arles, also in the south of France, at Pola in Istria, at Verona and at Pompeii in Italy are amphitheatres in a better state of preservation than the Colosseum. Their interior aspect

will be clear from the view of the amphitheatre at Verona, which is still used. The best preserved of the Roman circuses is that of Maxentius, on the Appian Way, two miles from Rome. "The external wall of masonry remains largely intact and the vaults which supported the seats though often ruined, are traceable." This structure was 245 feet wide and 1620 feet long.

It will be seen therefore that the Stadium on Soldiers Field is, in its external form, a combination of Greek stadium and Roman circus, shortened in proportion and carried out by means of a type of construction altogether modern, with which the external arcades, imitated from the ancient structures, are not wholly in keeping.

THE REGIMEN OF THE CHAGRES.

General Henry L. Abbot,

COLONEL CORPS OF ENGINEERS, RETIRED. LATE MEMBER, INTERNATIONAL TECHNICAL COMMISSION.

It is now well understood by those who have given technical study to the problem that facility of transit through the canal to be constructed across the Isthmus of Panama, in other words whether it is to be a good or a bad canal, will largely depend upon the plan adopted for the regulation of the Chagres River, whose valley it must follow through the greater part of the route, and which must furnish the needful water supply. The two essential elements to be considered are the control of the occasional great floods, and the frequent considerable freshets as well, so as to secure a waterway free at all times from currents and from more or less silt and sand deposits, and also to provide ample and safe storage for water reserves during the three or four months when the natural flow of the stream is insufficient for the needs of the canal. A definite knowledge of the regimen of the river becomes therefore highly important, and this has been secured by the elaborate and long continued investigations of the New French Company.

The Chagres traverses a basin clothed with the luxuriant vegetation of the tropics and subjected to rainfall and climate conditions so unlike those of the United States that it is not without interest to note the differences to be encountered. The Roanoke River affords a good standard of comparison. Above Neal, North Carolina, its drainage basin covers an area of about 8717 square miles, with an annual rainfall of about 51 inches. The corresponding figures for the Chagres are about 700 square miles and 112 inches. The Roanoke basin is largely covered by forests in the mountainous district, with swamps in the lower region; and in this respect the Chagres is not unlike, but the tropical growth is more dense. Both rivers are subject

to sudden oscillations in water level, but those of the Roanoke often cover several days while those of the Chagres rarely exceed twenty-four hours. The highest recorded flood at Neal attained, in March, 1897, a height of 30 feet above the extreme low water of September, the volumes being 83,000 cubic feet per second in the former and 2,000 cubic feet in the latter. The corresponding figures at Bohio, in November, 1879, were 40 feet and 113,000 cubic feet, the flood occurring as usual near the end of the year. The volume of the Roanoke at low stages up to about 13 feet above low water is larger than that of the Chagres, but above that level it is remarkably similar. Thus simultaneous gaugings for five months in 1896, made at Neal by the U. S. Geological Survey and at Bohio by the New French Company, indicated average volumes for that period of 5761 and 5849 cubic feet per second respectively.

The old popular belief that the regulation of the floods of the Chagres presents unprecedented difficulties, although often asserted, is erroneous. Thus the works of improvement now in progress upon the Warrior and its tributary the Black Warrior of Alabama, offer conditions far less favorable. At Tuscaloosa an extreme oscillation of 67 feet is of record, with a rise of 20 feet in 4 hours. The discharges range from 150 to 150,000 cubic feet per second. Such extremes have never been approached by the Chagres. All that is required for that river is a judicious plan of regulation.

The two chief branches of the Chagres head in the Cordillera de San Blas, the larger of them, the Pequeni, only about five miles from the Atlantic Coast. They unite just above Alhajuela, where is an excellent dam site. This upper sub-basin has an area of about 320 square miles, and consists of low mountain chains rarely exceeding 1500 feet above tide in height, and separated by narrow gorges. Near Alhajuela the river is bordered by water-carved limestone bluffs, in a few spots nearly white, and the region is of surpassing beauty. The next sub-basin extends to Gamboa, an air line distance of about nine miles. Here the river passes over many small rapids, and shows at low water stages bars sharply distinguished by sand, gravel, and

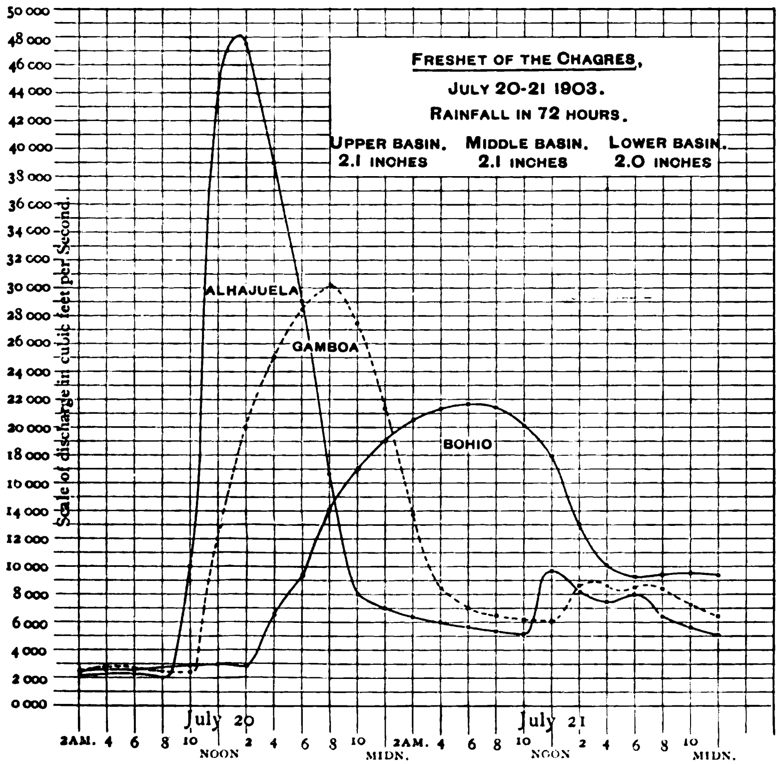
small bowlders, which are rarely if ever intermingled. The banks, often of rock, are occasionally subject to erosion in high stages of the river, and it is here that a small amount of sedimentary matter is then collected. The bars are, of course, at such times slowly pushed down stream toward the canal route near Gamboa. The lower sub-basin extends thence to Bobio, an air line distance of about fifteen miles, covering an area of about 250 square miles. Here the slope of the bed is rapidly reduced, and tide level is reached, at the lowest river stage, near the Bohio bluffs, where will be placed a dam flooding the valley to Gamboa and constituting part of the route for shipping. Thence to Colon, about fourteen miles, this route will be formed by a canal quite separated from the river and at tide level. After leaving the Chagres near Gamboa the canal passes through the Emperador and Culebra cuts and then descends by locks to the Pacific near Panama. When considering the regulation of the Chagres for canal purposes it is therefore only needful to take into account the three sub-basins above described, bearing in mind, however, that in the largest floods the district below Bohio has always been deeply submerged, and that the canal must be protected against this danger by suitably regulating the outflow from Lake Bohio.

The New French Company, warned by earlier experience, has been keenly alive to the importance of a thorough understanding of the conditions of this hydraulic problem before undertaking work upon a large scale. Admirable measures for this purpose have been taken, and all important facts are now known. For many years, continuous automatically recorded water heights have been kept at Alhajuela, Gamboa and Bohio, with thousands of gaugings to translate such records into corresponding river discharges. The region has been contoured carefully, to define the border of artificial flooding at different lake levels. Long continued rain records at many sites have been kept; and observations to determine temperature, barometric pressure, and seismic disturbances have not been neglected. An elaborate study of these data has been made, and few rivers even in densely populated regions are now better

understood than the Chagres, — thanks to the intelligent work of the New French Company under the administration of Monsieur Maurice Hutin, the Director General, and Monsieur Louis Choron, the Chief Engineer. The general conclusions reached may be summed up as follows.

The river supplies ample water for all possible needs of the canal if proper provisions are made for that purpose. The largest floods may be controlled, and a route for shipping wholly free from annoying currents or deposits may be secured by two dams, one at Bohio and the other at Alhajuela, the lake formed by the latter affording secure storage for the reserves to meet the needs of the canal in the low water season, which includes three months (February, March and April). Any possible flooding of the district below Bohio may be prevented by introducing the system of overflow weirs in successful use on the Manchester Ship Canal. Ample water power for lighting the canal and mechanically operating it will be supplied at the dams.

Considering the hydraulic problem in more detail it may be said that the regimen of the Chagres is governed by the tropical conditions of its drainage basin. The annual rainfall is about 112 inches, being about 5 inches for the three dry months and 107 inches during the rest of the year. The corresponding annual outflow is about 3800 cubic feet per second, ranging in different years from a minimum of 3400 to a maximum of 7000 cubic feet. The tri-monthly low water discharge is about 1000 cubic feet per second, the minimum of record (1901) being 750 cubic feet of which 530 cubic feet passed at Alhajuela. The flow during the dry months is gentle and nearly uniform, but during the rainy months freshets are always to be expected, to say nothing of the rare great floods, of which there have only been six in the past half century. These freshets are caused by the sudden down pours of rain which often last two or three days. The rises are short lived but violent, as may be seen from the example, by no means extreme, shown in the following table. The plate is added to present it more clearly to the eye.


FRESHET OF THE CHAGRES,
JULY 20-21 1903.
RAINFALL IN 72 HOURS.
UPPER BASIN. 2.1 INCHES
MIDDLE BASIN. 2.1 INCHES
LOWER BASIN. 2.0 INCHES
ALHAJUELA
GAMBOA
BOHIO
Scale of discharge in cubic feet per Second.
50 000
48 000
46 000
44 000
42 000
40 000
38 000
36 000
34 000
32 000
30 000
28 000
26 000
24 000
22 000
20 000
18 000
16 000
14 000
12 000
10 000
8 000
6 000
4 000
2 000
0 000
July 20
July 21
2A.M. 4 6 8 10 NOON 2 4 6 8 10 MIDN. 2A.M. 4 6 8 10 NOON 2 4 6 8 10 MIDN.

FRESHET OF JULY 20–21, 1903, IN THE CHAGRES.

Hours	Height above sea in metres July 20	Height above sea in metres July 21	Discharge in cubic feet per second July 20	Discharge in cubic feet per second July 21
	Alhajuela			
2 A. M.	28.64	29.20	2119	6357
4	28.66	29.14	2225	5933
6	28.66	29.10	2225	5651
8	28.63	29.07	2084	5439
10	29.70	29.03	10136	5191
noon	32.80	29.66	43934	9810
2 P. M.	33.15	29.45	48560	8193
4	32 40	29.37	38778	7593
6	31.60	29.42	29066	7946
8	30 40	29.17	16352	6145
10	29.45	29.10	8193	5651
mid't	29 28	29.01	6922	5050
	Camboa			
2 A. M.	14.80	17.00	2613	13844
4	14.90	16.00	2931	8617
6	14.88	15.64	2861	6957
8	14.80	15.54	2613	6534
10	14.78	15.48	2543	6286
noon	17.10	15.42	12009	6004
2 P. M.	18.00	16.00	19919	8617
4	18.76	16.00	25004	8617
6	19.28	15.90	28712	8158
8	19.48	15.90	30160	8158
10	19.08	15.70	27264	7240
mid't	18.20	15.56	21225	6604
	Bohio			
2 A. M.	1.31	5.10	2543	20448
4	1.32	5.20	2578	21119
6	1.35	5.28	2649	21684
8	1.42	5.27	2790	21614
10	1.47	5 05	2931	20130
noon	1.47	4.70	2931	17835
2 P. M.	1.42	3 80	2790	12820
4	2.40	3.20	6746	9959
6	3.40	3.00	9078	9112
8	4.06	3.06	14162	9359
10	4.55	3.10	16952	9536
mid't	4.89	3.08	19071	9465

To form an intelligent idea of the provisions to be adopted for controlling the flow of so variable stream it is needful to study the volumes that, without regulation by a lake above, may be expected to strike the canal route near Gamboa and to traverse the artificial lake extending from that point to Bohio. The following table has been prepared to give this information. The question of the proper measures for controlling the great floods has been fully discussed in a paper which appeared in 'The Engineering Magazine' for December, 1902, and space forbids a consideration of the problem here, but a few figures relative to these floods have been added to the table to facilitate comparison between them and the freshets.

It should be borne in mind that these freshets often occur three or four times in each month from May to January inclusive, and that as many as ten in a single month are of record. As stated above they are caused by sudden downpours common in the rainy season, which often last three or more days and cause rapid rises in all tributary streams throughout the basin. High rises of the Chagres, however, rarely continue more than about 24 hours, and that period has been adopted as the standard of duration, selecting the hours so as to show the maximum daily flow. The list has been chosen from a wealth of examples to illustrate three characteristic types, determined by the locality in the basin which receives the larger part of the rainfall.

These freshets sweep down the bed like great waves, the crest traversing the eleven miles by river separating Alhajuela from Gamboa in about 4 hours, and the 20 miles by river thence to Bohio in about 7 hours. The table gives both the average and the maximum volume at each locality, as well as the rainfall in each sub-basin to which it was due, as nearly as this latter can be estimated from the daily records. In comparing different freshets and corresponding rainfall it must not be forgotten that the average volume is largely dependent upon the stage of the stream when it received the addition, and hence that maximum volumes furnish a better criterion. The average volumes are added to afford data for estimating the

total contributions during the twenty-four hours, under the actual conditions then existing.

TYPICAL FRESHETS AND FLOODS OF THE CHAGRES, CLASSED BY LOCUS OF RAINFALL.

Date	Rainfall in sub-basin in 72 hours.			Discharge in cubic feet per second, for 24 hours.					
				Alhajuela		Gamboa		Bohio	
	upper, inches	middle, inches	lower, inches	average	maximum	average	maximum	average	maximum
	Rainfall chiefly in upper basin.								
May, 1899	6.0	0.3	1.8	10 348	30 725	9 641	20 484	10 807	17 588
Aug., 1900	3.9	1.7	1.3	10 383	22 850	10 736	20 625	14 374	18 612
Aug., 1903	4.7	3.2	1.5	11 760	30 831	17 270	25 922	21 402	27 547
Nov., 1903	3.4	1.3	1.9	24 581	44 252	24 192	35 348	30 831	36 305
means	4.5	1.6	1.6	14 268	32 173	15 469	25 675	19 354	25 004
	Rainfall chiefly in lower basin.								
Dec., 1900	1.1	0.8	2.6	14 762	23 486	14 974	21 932	18 259	22 885
Jan., 1902	1.2	4.1	7.7	19 389	23 945	22 532	26 629	37 153	38 107
Dec., 1903	1.6	3.0	3.4	5 898	6 922	9 641	14 339	20 307	22 391
means	1.3	2.6	4.6	13 350	18 117	15 716	20 978	25 251	27 974
	Rainfall well distributed.								
Aug., 1899	1.5	1.3	1.1	15 080	29 771	16 634	26 205	19 919	25 887
Nov., 1899	2.5	3.9	3.1	11 160	30 937	12 855	23 132	18 859	24 333
Oct., 1900	3.0	3.6	1.9	11 549	26 805	14 621	23 521	16 528	20 837
Nov., 1901	6.0	4.5	6.1	11 301	19 071	16 917	25 075	28 995	33 233
same	2.6	1.8	2.1	13 738	22 497	15 116	21 296	24 474	26 699
same	4.8	2.9	4.6	21 119	43 581	25 357	36 871	33 727	40 508
Aug., 1902	1.3	1.6	2.3	11 725	30 231	14 415	23 803	14 586	19 777
Oct., 1902	2.4	2.0	2.2	11 725	26 805	15 998	26 629	18 683	24 262
July, 1903	2.1	2.1	2.0	18 788	49 231	17 411	30 160	17 305	21 684
Dec., 1903	3.5	3.0	3.2	14 550	19 989	11 725	14 339	17 870	19 623
same	2.8	3.0	3.0	9 747	16 917	12 679	19 354	19 777	21 826
Jan., 1904	2.0	1.3	1.5	11 902	22 179	13 102	22 461	13 809	16 881
means	2.9	2.6	2.8	13 526	28 147	15 575	24 545	20 378	24 616
	Two older freshets and the six floods.								
Dec., 1888	—	—	—	—	—	30 8[illegible]7	40 014	—	—
May, 1897	—	—	—	—	—	39 549	42 380	—	—
Nov., 1879	—	—	—	—	—	—	78 615	—	112 731
Nov., 1885	—	—	—	—	—	57 001	64 488	—	74 801
Dec., 1885	—	—	—	—	—	40 7[illegible]5	44 923	—	47 501
Dec., 1888	—	—	—	—	—	51 809	58 202	—	79 004
Dec., 1890	—	—	—	—	—	50 185	65 371	64 347	71 657
Dec., 1893	—	—	—	—	—	39 449	43 157	48 490	51 068

The entrance to the projected lake below Gamboa is for a few miles rendered narrow by bounding hills, and it is believed that a study of the data contained in this table, which may be largely increased from the records of the French Company if desired, will convince hydraulic engineers that such volumes, carrying as they do more or less sand and gravel, should be excluded from a great trade route to be used by ocean steamers. By a lake at Alhajuela to regulate the flow, the river may readily be transformed into a stream as gentle as it now is in the dry season; but strange as it may seem this lake was not regarded as essential by the Isthmian Canal Commission.

Some interesting facts as to stream flow in this region may be gleaned from this table. Thus in freshets resulting from a rainfall well distributed over the basin, the larger maximum flow occurs at upper stations, and this usual river rule is naturally more pronounced when there is a larger relative downfall in the mountain district; in the opposite case the rule is reversed. Nevertheless, although unfortunately no great flood data have ever been collected at Alhajuela, it is apparent from the measurements below that at such times when widespread and long continued downpours prevail, and the entire region is surcharged with water, the rule is reversed. In every recorded instance the discharge at the height of the flood was greater at Bohio than at Gamboa. This fact is probably in part due to peculiar conditions governing the local slope at such times. At the lowest stage the level of the ocean is here nearly attained, and as the water rises the local slope rapidly increases, and is sustained by flow from a large district just above which is then always inundated. Above, near Gamboa, there is a considerable natural slope to the bed, and this furnishes reserves as the water rises, limiting the height attained and hence the maximum volume. The extreme oscillation at Bohio is greater than at any other known point of the valley.

One important characteristic of the regimen of the Chagres remains to be noted. To verify the geological indications that no excessive percolation is to be feared in the artificial lakes to be created, a careful study has been made to determine what

becomes of the rainfall in this drainage district, a problem which the elaborate measurements rendered it possible to submit to analysis. Space here is lacking for details, but they will be found in the Monthly Weather Review for February, 1904. Conditions on the Isthmus are specially favorable to such studies. Ice and snow are unknown. The extraordinary uniformity of the temperature throughout the year, and the sharp division between rainy and dry seasons, regulate evaporation in a manner to eliminate the irregular variation common in temperate regions. The country is clothed with dense tropical vegetation and is in its natural state. Lastly, we have a definite knowledge of the daily rainfall and corresponding outflow for a period of six years.

The general conclusions resulting from the study are the following. Of the annual rain which falls from the clouds about 34 per cent is evaporated, or absorbed by plant life, or sinks permanently into the earth. During the rainy months this loss is probably about 50 per cent, the excess being explained by the larger wet surface then exposed to evaporation, which latter during the dry season is much reduced by lack of material. Furthermore of the annual rainfall about 29 per cent at once escapes to the river and flows off by its bed, and the remaining 37 per cent after a delay of perhaps about three months percolates through the earth and augments the flow through the beds of the streams, as ground water. During the three dry months fully three quarters of the actual flow must be ground water, the measured outflow then exceeding the entire rainfall. Nature thus supplies a useful reserve to assist in meeting the needs of the canal at this critical period.

Comparing these figures with those resulting from similar investigations in the northern and eastern parts of the United States, covering the watersheds of a dozen rivers and streams, it appears that the catchment basin of the Chagres in round numbers exhibits in inches per square mile 2.5 times the rainfall, 3.3 times the outflow, 1.5 times the evaporation; and that ground water plays a much more important part in the regimen.

WASHINGTON, D. C.
April 7, 1904.

HARVARD ENGINEERING JOURNAL.

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Engineering Laboratory Notes.

The graduates may be interested in a brief mention of some of the work, outside of the regular courses, that has been going on in the laboratory during the year.

Samples of steel-concrete in various shapes, made from the

material used in the Stadium, were tested in room 2 for ultimate strength by Prof. Johnson.

The Goldschmidt Thermit Company presented the laboratory with a length of girder rail containing a joint welded by thermit, a mixture of metallic aluminum and iron oxide. The electrical students tested it for conductivity.

A 15 h. p. variable speed transmission gear, loaned by the Power & Speed Controller Company, has been under test by the mechanical seniors, as described by Prof. Marks in the last Journal.

A. D. Wilt, '03, made some tests on special tool steels, in connection with his work at the National Cash Register Co. of Dayton, Ohio.

Tests were made in the photometrical laboratory by Mr. Whiting on the Rettish Burner, an improved type of gas burner designed for use with incandescent mantles.

The Automatic Electric Company has presented the laboratory with a complete working equipment of their automatic or girl-less telephone system. The set comprises six subscriber's phones and an exhibition switchboard containing the machines which replace the central operator. The board has first selector, second selector and connector switches so that the operation of a 10,000 subscriber exchange is illustrated in the model. The system is now being set up for intercommunicating service by some of the electrical seniors.

Several of the new Edison automobile cells are being tested in room 107. Prof. Kennelly will present a paper on this cell before the International Congress at St. Louis this summer.

The hydraulic students under Prof. Hughes made measurements of the loss of head in 1000-ft. lengths of fire hose which were borrowed from the Cambridge Fire Department.

D. N. McClinton, '04, and C. E. Tirrell, '04, are carrying out investigations of two 36″ Davidson fans which have been presented recently to the laboratory by the Mass. Fan Co.

L. A. Hackett, '04, and W. M. Stone, '04, are working on a device for obtaining a continuous time record of the pressures existing in a gas engine cylinder. They will use this record to

study the explosive phenomena under various conditions of operation.

G. Johnson, '04, A. G. Thomas, '04, H. K. Roberts, '04, and H. W. Smith, '04, are engaged on a series of tests of a 3-cylinder, 35 h. p. gasoline Westinghouse engine.

A. A. Thayer, '04, is determining the strength of several of the new high speed tool steels, both when annealed and hardened.

A. Tyng, '04, is investigating the specific heat at constant pressure of superheated steam.

D. C. Barnes, '04 and F. H. Poor, '04 have been investigating the ventilating effect of the air brake exhaust on railway motors.

Graduate Notes.

At the March meeting of the President and Fellows of Harvard College, F. L. Kennedy, A. B. 1892, S. B. 1898, was appointed Asst. Prof. of Mechanical Drawing.

H. C. Ward, '99, is proprietor and manager of the Greenfield Electric Light & Water Plant, at Greenfield, Tenn.

R. A. White, '99, is with Ford, Bacon & Davis of N. Y., at Birmingham, Ala. He is engineer for the Birmingham Street Railway & Power Co.

Edward J. Whittier, '01, is with the American Agricultural Chemical Co., supply department, 26 Broadway, New York.

Herman F. Tucker, '01, is assistant engineer on the Harvard Stadium.

Daniel Armistead, '99, is with the Allis-Chambers Company in the engineering department of the Edward P. Allis Works, Milwaukee, Wis.

J. H. Libbey, '98, is assistant engineer for the Boston & Northern R. R., with offices at 86 State St., Boston.

R. F. Blake, '99, is with the Fore River Ship and Engine Co., Quincy, Mass.

Stanley Cunningham, Jr., '00, is with the National Tool and Machine Co., South Boston, Mass.

A. D. Wilt, '03, has charge of the engineering laboratory of the National Cash Register Co., Dayton, Ohio.

F. Pope, '01, has just returned to Boston after spending a year at the mines near Johannesburg, South Africa.

Architectural Notes.

On Friday evening, May 6th, the Boston Society of Architects paid a visit to Cambridge, meeting first at Pierce Hall to see the Engineering building and its equipment, and then stopping at Robinson Hall for a brief inspection of the home and some of the work of the Department of Architecture. Keen interest was apparently taken in those aspects of the preliminary training of an architect which can best be obtained in a school. More than one practitioner of established position and long experience was heard to envy the young men who were having their introduction to the profession in such agreeable surroundings as those provided by the gift of Mr. and Mrs. Robinson.

The models of vaulting in the basement, which were made largely by the students in the course in Mediaeval Architecture last year, excited a good deal of interest and discussion, as did also the exhibition of the work of the course in the Theory of Design by pupils of Dr. Denman W. Ross. There was a very complete exhibition of examples of the underlying principles of design in two dimensions, and fortunately also many fine examples of their application.

The Society afterwards dined at the Colonial Club and was addressed after dinner by President Eliot, Mr. R. S. Peabody, President of the Society, Prof. Hollis of the Engineering Department, and Prof. Warren, of the Department of Architecture. The interesting question of the employment of architects for the designing of University buildings was opened by President Eliot, and discussed by the other speakers. In the course of his remarks President Eliot expressed the idea that possibly the architect, like the sculptor, painter, and musician, was most successful when his work expressed only his own conception.

Mr. Peabody and Prof. Warren, on the other hand, stated that to them architecture seemed essentially a work of co-operation, and convincing historical evidence was presented by them. A suggestion made privately to President Eliot by Prof. Warren was approved by the other speakers and apparently by the Society as a whole. This was that in the future the design for a new University building should, before its execution, be criticised by all those architects who have previously been employed by the Corporation in the erection of buildings. It is understood that the original design would then be modified to accord with the judgment of this board of critics. By this means it is hoped to give that much desired unity to the aspect of the University which has hitherto been lacking, but which has begun to be felt in the work recently done by Messrs. McKim, Mead & White, and others.

Prof. Hollis spoke in an interesting way about the successful use of concrete in the Harvard Stadium, and in conclusion urged that the engineers and architects should come into closer relations socially as well as professionally by locating their societies in the same building.

After this the Society adjourned to the Germanic Museum, where Prof. Francke personally conducted the party most delightfully among the fine casts and replicas of the examples of German architecture and sculpture of the best periods.

C. R. Wait, '03, A, who has just completed a year of graduate study in architecture at the University, has just taken the examination for the Nelson Robinson Jr. Travelling Fellowship in Architecture.

H. D. Grinnell, '03, A, is at present in the Boston office of Messrs. Cram, Goodhue and Ferguson, as are also Gordon Allen, '98, and S. B. Parker, '05.

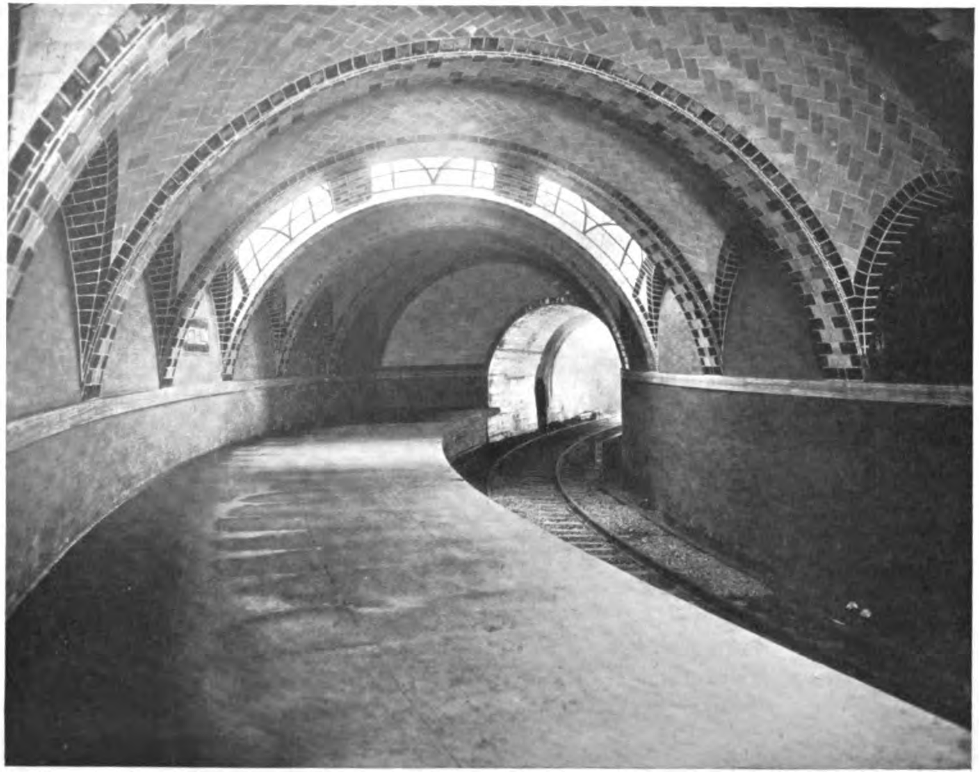
D. D. L. McGrew, '03, was at last reports in the Boston office of Messrs. Parker and Thomas, the architects of the new Racquet Club on Boylston Street, a very successful design in brick and terra cotta.

E. M. Parsons, '03, was at last reports in the office of Messrs. Wheelwright and Haven in Boston.

C. M. Bill, '00, is a designer in the employ of Messrs. Alley and Emery, interior decorators, in Boston.

A. S. Walker, '98, A, is in the office of Mr. Whitney Warren in New York City.

F. M. Jones, '00, A, is in Springfield, Mass., in charge of some work for Messrs. Peabody and Stearns of Boston.



THE GUSTAVIUS TILE ARCHES AT THE CITY HALL STATION.

HARVARD ENGINEERING JOURNAL

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VOL. III NOVEMBER, 1904 NO. 3

THE STATIONS OF THE FIRST RAPID TRANSIT RAILROAD OF THE CITY OF NEW YORK.

By Daniel Lawrence Turner, C. E.

It is difficult to impress one with the magnitude of the Rapid Transit Railroad unless a trip has been made through it. Even more difficult is it to convey an adequate idea of what the stations are really like — particularly those in the underground portion of the railroad. Dark, grimy and poorly ventilated, has aptly described most tunnels heretofore constructed. One naturally imagines such a description equally fitting for the stations of an underground railroad. The New York "Subway" stations, however, have none of these characteristics. They can hardly be compared with the stations of any other similar railroad. They afford landing places for passengers — and provide means for ingress and egress — these are the only features they have in common with the stations of the London, Glascow and Liverpool underground roads; the Métropolitan of Paris; Budapest Railway; or even the Boston Subway.

Entering a station from the street a few steps bring you to the platform and the ticket booth. You are hardly conscious of being underground, for the daylight has followed you. Purchasing a ticket from the booth immediately at hand, you pass the ticket chopper and reach the train platform. Looking across the four tracks, between the rows of columns separating them, the opposite platform can clearly be seen. There a num-

ber of passengers are awaiting a train travelling in the opposite direction from that in which you expect to go. Suddenly, with a rumble and a whir, your view is shut off. An express train has passed. Looking up and down the tracks, a few blocks away in either direction, a bright spot of light appears through the semi-gloom of the intervening subway. One of these spots indicates the location of another local station similar to the one upon which you are standing; the other, perhaps an express station, where the train which has just passed will stop. Travelling to that station on the first local train coming along, you may board the next express. Observing your surroundings, meanwhile, you find that the roof of the station is only a few feet below the street, for nearly half of the ceiling is constructed of glass through which the sunlight streams. The remaining portion is of white cement divided into panels with ornamental moldings. The side walls are covered almost entirely with white glass. Their surfaces being broken up into panels with colored mosaic pilasters and friezes. A faience or terra cotta cornice finishes off the top of the wall. Mosaic name tablets incorporated in the wall design designate the station. To withstand the greater wear to which the base of wall will be subjected, a wainscot of light colored brick has been provided. The floor is constructed of cement of a light gray color. All other details of construction and equipment are in keeping. Such, briefly, are the New York Subway Stations — bright, airy, and finished in every detail. Obviously, other considerations than the purely utilitarian requirements of a railroad station have affected their design. It has been sought to make them attractive and decorated in a manner befitting a great public work.

While this paper is to be devoted mainly to a description of the stations, a few words concerning the railroad itself will not be amiss.

This road is the first of those great arteries of travel which are destined to convey its throbbing life from the outermost limits to the heart of the Great City. No other similar railroad is so great in extent as this first Rapid Transit Railroad of the City of New York. It traverses the streets of the city for a distance

of nearly twenty-one miles, and, a still more important feature to the public, over six miles of the road contains four tracks, side by side. For its remaining length it is two and three tracks in width. The four parallel tracks provide for a service of fast trains making stops at long intervals, as well as the ordinary service of slow trains stopping at short intervals. Though this railroad is only a part of the great system which has already been outlined, its route is an extensive one. It begins opposite the Post Office, at the intersection of Park Row and lower Broadway, and extends north on Park Row, Centre and Elm Streets, Lafayette Place, and Fourth Avenue to 42nd Street; thence across town along 42nd Street to Broadway, then up Broadway to 104th Street. At this point the road separates into two branches: The west Branch continues up Broadway to Fort George, thence along Kingsbridge Road to Kingsbridge; the east branch extends under 104th St., Central Park, Lenox Avenue, Harlem River, and East 149th Street to Third Avenue, thence along Westchester Avenue, Southern Boulevard, and Bostin Road to the Bronx Park. The main line and each of the branches are approximately seven miles long.

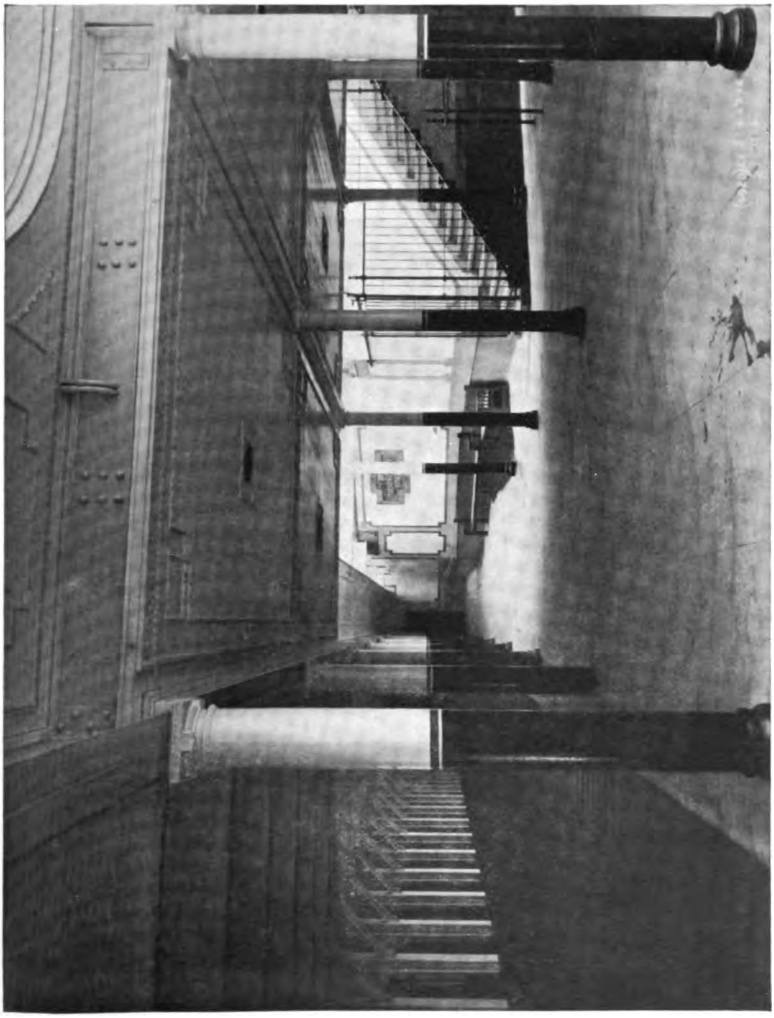
For the construction, equipment and operation of this epoch making railroad, the largest single contract ever entered into, was executed between the City and the Contractor. Its amount was $35,000,000.00.

Although there are forty-nine stations, they are distributed over the twenty-one miles of railroad, extending from the southern end of the City to its extreme northern limits. The railroad has been constructed in several different ways. Each type of construction has its accompanying station type. The greater portion of the road is built as near the street surface as possible, commonly called the "Subway" type of construction. Though this tppe necessitates the excavation of the street surface, and the rearrangement of all underground pipes and conduits, and thereby subjects the public to the annoyances incident to these operations, it has several particular advantages. By following this plan the stations are brought immediately beneath the street surface, making them light, well ventilated and easily accessible

by short flights of steps. Again, some portions of the road have been constructed at a considerable depth below the surface, in tunnel. The remainder is erected over the street on an elevated structure. The amount of each type is as follows:— Subway, 10.5 miles; Tunnel, 4.5; Elevated, 5.8 miles. Thirty-four of the stations are located in the Subway portions of the road, three in the Tunnel, and twelve on the Elevated structure.

The stations are not evenly distributed over the entire line. The intervals between them are shorter in the commercial districts where there is greater congestion than in the less crowded residential districts. Segregating the commercial and residential stations, we may for convenience designate them as down-town and up-town stations respectively. The interval between the former is about five blocks, or $\frac{1}{4}$ of a mile; between the latter about ten blocks or one half mile. The fourteen stations below and including the 50th St. station belong in the down-town class. The 35 stations above 50th Street station are in the up-town class. In the morning hours the passengers board a train at the larger number of up-town stations and leave them at the fewer down-town ones. In the afternoon the operation is reversed. In consequence of this, the down-town stations have had to be provided with facilities for handling a greater number of passengers. Their design, therefore, has been affected accordingly.

Again, one of the most noteworthy features of the railroad is its unequalled facilities for providing the public with an express train service from one end of the City to the other, during all hours of the day. This is accomplished by means of the four track main line, already alluded to, extending from the post office to 96th Street. The two inner tracks are used for the high speed, or express trains; the outer ones for the slow running, or local trains. The local trains stop at all stations, while the express trains stop at specially designated express stations. These latter stations are located at Brooklyn Bridge, 14th Street, Grand Central Station, 72nd and 96th Streets. In other words the express trains make stops at about every fifth station up to 96th Street, or at intervals of about one and one half



GRUEBY FAIENCE CORNICE AND NAME TABLET, STAIRWAY, CEILING, AND RAILINGS OF THE 28TH STREET STATION.

miles. Above this point, on the east and west branches, either express or local trains stop at the regular local stations, at the usual one half mile interval. The train service provides for eight car trains running two minutes apart on the express tracks, and five car trains running one minute apart on the local tracks — each way. The express trains are scheduled to travel at the rate of thirty miles per hour, including stops; the local trains at fifteen miles per hour. At these rates a person can go from the Post Office to 96th Street in less than fifteen minutes, or to the end of either the east or west branches within thirty minutes.

It appears, then, from what has already been said, that the design of the stations is affected by a number of very different considerations. It is in satisfying these several requirements that the various types of stations have been evolved. From an operating point of view, there are two general classes, — local and express stations, irrespective of any other characteristic features; all stations belong to one or the other of these two types. Then, too, the prospective traffic to be provided for due to the environment of the stations has effected their design. There are up-town and down-town stations. Again, there are elevated, tunnel, and subway stations. Each type differing from the other on account of the variations in the construction of the railroad. Also, the stations have been grouped into classes, having the same general architectural treatment. And finally there is a class of stations which have some peculiar feature in their design; these belong to the unique type. While the above general classifications are possible, it must not be inferred that each station is an exact counterpart of any other of the same type. As a matter of fact a separate study and design for each of all the forty-nine stations has been made. It has been necessary to do this, in order to adapt each station to the varying physical conditions existing at its point of location.

The plan of all stations includes a ticket-room, train-platform, and facilities for reaching the station level from the street surface. The ticket-room may be entered from the street without the payment of a fare; here the ticket booth is located. This

portion of the station is separated from the train-platform by railings; the passage way between the two is controlled by the ticket chopper. Passengers enter and leave the trains from the train-platform. For all local stations below 96th Street the platforms are 200 feet long, for all express stations and the stations above 96th Street they are 350 feet long. The shorter platforms will accommodate the five car local trains to be operated between the City Hall and the 96th Street Station. The longer ones will accommodate the eight car express trains which will run as local or express trains above 96th Street to the two extremities of the road. No platforms are less than 9 feet wide at the narrowest point. All of the Subway Stations have been constructed as near the street surface as possible. This enables the station platforms to be reached, in most cases, by short stairways. The tunnel stations are approximately 98, 120 and 46 feet below the street surface. Their platforms are reached by means of two elevators which have a combined capacity of about 3500 persons per hour. In addition to the elevators a stairway is provided for emergencies. All of the elevated stations are accessible by stairways. One, however, the Manhattan Street Station, which is about 50 feet above the street, has been provided with an up and down escalator.

Usually the train platforms are level for their entire length; this requires the tracks, too, to be level, opposite the stations — particularly the tracks used by the trains stopping at the station. These level stretches are obtained by raising the road bed above the elevation that would exist if the grades were continued unbroken past the station. Trains generally arrive at the level on an ascending grade and depart on a descending one. Their speed is thereby retarded upon approaching a station and accelerated upon leaving it. The level enables the train to be started quickly after the stop has been made. The station stop therefore requires a minimum expenditure of time. The grades on the express tracks, on the other hand, are continuous through local stations, — in consequence of this, these tracks are often several feet below the level of the local tracks.

Most of the underground stations are very well provided with

natural light. Twenty-four of the thirty-seven stations will require very little artificial light during the daytime. These stations are all located in the Subway portion of the road. This is one of the particular advantages of this type of construction. The daylight is obtained through glass roofs constructed over all portions of the station which are under sidewalk areas. Even at night, should the artificial light fail, enough light will reach the stations to prevent the same from becoming absolutely dark. The artificial light is furnished by incandescent lamps, attached to wall or column brackets, or sunk into recesses in the ceiling. The current for most of the lamps is obtained from a regular lighting circuit. To provide for emergencies, however, a number of lamps can be lighted from the track circuit — thus providing two independent sources for artificial lights. The lights are all controlled from a central point. The switch board is usually located in the ticket booth, in easy reach of the ticket seller.

The local stations usually have two platforms. The passengers enter or leave the north bound trains from one and the south bound trains from the other. These platforms are located on the outer sides of the local tracks, so that all tracks pass between them. They are extended out under the sidewalks on each side of the street as far as the width of the streets will permit, each platform being entered from its own side of the street. In most cases no provision is made for crossing from one side of the station to the other without going to the street surface. At the Astor Place and Times Square Stations, however, passageways under the tracks permit passengers to enter the station on either side of the street and cross over to the opposite side. At five other stations — the 103rd, Columbia University, 168th and 181st Streets, and Mott Avenue Stations — passageways over the tracks but under the street surface permit one to cross from one platform to the other. At these stations, though, only one street entrance is provided. The north and south bound passengers use a common entrance from which they reach the transverse passageway and then go down to either train platform.

The main variation in the several station plans occurs in the ticket-room portion of the station. The outline of the train-platform changes very little. There are three different types of subway local stations, and several stations of special design. The 28th Street Station is typical of the first type of all down-town stations. Its plan is symmetrical about the cross street and the street traversed by the railroad. The train-platforms are usually directly opposite each other, and are built partly under the roadway and partly under the sidewalk. They are about 15 feet wide at the center and narrow to about 9 feet at the extreme ends. The ticket-room extends under the cross street. It is about 50 feet wide and its length corresponds to the full width of the street between the building lines. The ticket booths, toilet rooms, and service closets are located in this space. Four stairways are provided on each side of the station, two to be used exclusively for entrance stairways and two for exits. This is the main feature of all down-town stations. The entrance stairways reach the station at the rear wall of the ticket-room, descending towards the train-platform. Passengers enter, purchase their tickets at the booth immediately at hand, and pass forward in a direct line by the chopper to the trains. The exit stairways leave the station directly from the train-platform, ascending to the street away from it. When a train stops at the station those passengers leaving it pass at once to the street without going through the ticket-room. With this arrangement, the greatest facilities are provided and the incoming and outgoing lines of travel do not meet or interfere with each other. Both the entrance and exit stairs land at the surface, close to the curbs, on the sidewalks of the cross-street — two on the north side and two on the south side.

The second type or up-town stations on the Broadway portion of the line are similar to the 66th Street Station. The main difference between the plans of this and the down-town stations is due to the lesser facilities required. The ticket-room is only excavated under the cross-street to a sufficient depth to enable one wide stairway to be provided on each platform. The street entrances to the stairways are located on the Broadway side-

walks, on the diagonally opposite corners, instead of on the cross-streets as heretofore described. As before, the entrances are as close to the curb as possible and parallel to it. Each stairway is used by passengers entering and leaving the station. If the increase of traffic requires it an additional stairway can be constructed on each platform.

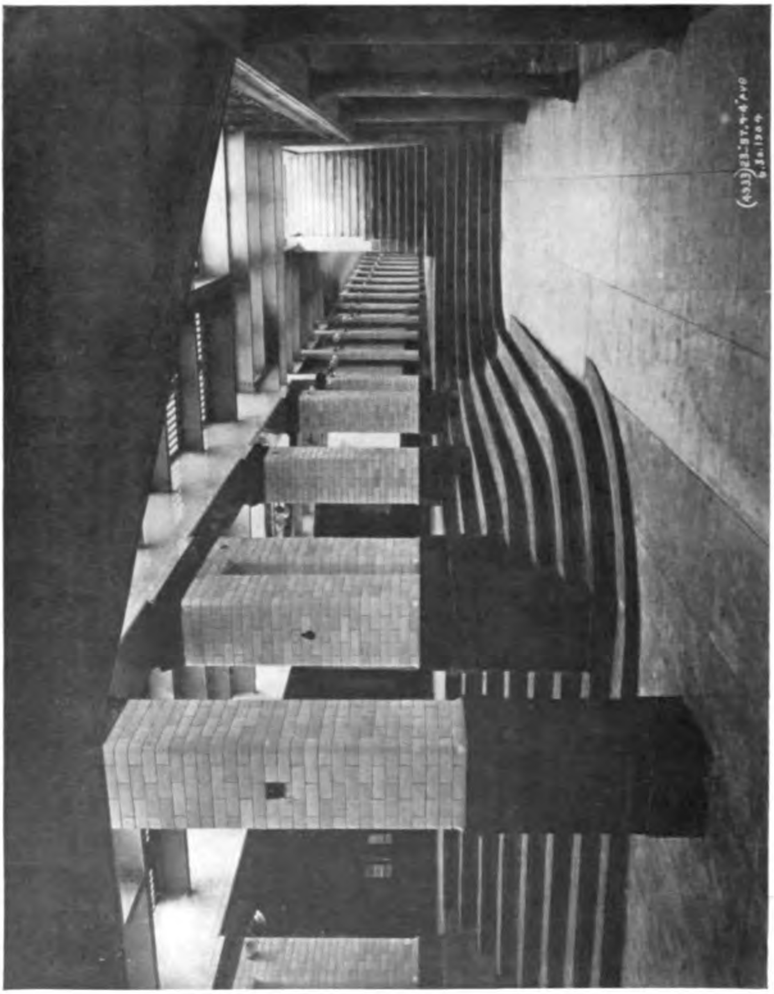
The stations on the Lenox Avenue branch belong to the third type — 135th Street is representative of these. Their plan is not symmetrical about the center-line of the tracks because the center-lines of the Subway and street do not coincide. These stations are located in the Harlem business district, therefore anticipating greater traffic than the Broadway stations will have, two stairways have been provided on each platform; both will be used as entrance and exit stairways.

The City Hall Station is unlike any other one. It is located on a single track loop traversed by all local trains, travelling only in one direction. It has one train platform. The ticket house is below the street surface but not as low as the train platform. Two stairways enter the ticket house, from which point a single wide stairway descends to the train level. The 103rd and Columbia University Stations are also of special design. They differ from the other stations heretofore described in that the ticket-room is located in a house constructed on the street surface. The house is located in the park area in the center of the street. The single entrance admits passengers to both train platforms. The station at 110th and Lenox Avenue has only one "island" train-platform. At this point it was impracticable to obtain access to two platforms located outside of the tracks in the usual manner. The north-bound trains stop on one side of the island platform and the south-bound trains on the other.

All of the express stations are located in the Subway portions of the railroad. In consequence of this they are easily accessible and well lighted with natural light. At these stations the local and express tracks separate and two "island" platforms are located between them. The local trains stop on the outer sides and the express trains on the inner sides of these platforms.

At three points — Brooklyn Bridge, 14th and 96th Streets — the stations have local as well as the island platforms. All of the platforms are connected, either by overhead or underground passageways, so that passengers may transfer from one train to another at these points. At Brooklyn Bridge and 14th Street the entrance and exit stairways lead from the sidewalks to the ticket-room, which is beneath the street surface. At the level of the ticket-room floor a transverse passageway crosses over the tracks and local and island train-platforms, but beneath the street surface. Short flights of steps descend from the passageway to the train platforms. The Grand Central and 72nd Street stations do not have local platforms. Passengers entering the former station, descend to ticket-rooms located on mezzanine platforms at either end of the station. From the mezzanine level stairways go down to either the up or down town "island" platforms. At the latter stations the ticket room is located in a building on the street surface. From the ticket-room passengers may descend directly to either train platform. At 96th Street the ticket-room local and island platforms are on the same level. To cross from one to another passengers descend to a transverse passageway crossing under the platforms and tracks, instead of over them as in former cases.

The occupants of a number of the new buildings and hotels being erected along the route of the subway may enter the adjacent stations through basement passageways without going on the street. In some instances the building owners have sought and obtained permission to open the entire basement stories into the stations, thus providing ample show window space and commodious entrances through their buildings. The principal advantage of this feature is that it enables the stairway obstructions on the street to be reduced to a minimum, if not entirely eliminated. As the property holders awake to the value of such connections they are filing applications for permission to make them. Already connections have been made with the Staats Zeitung Building at the Brooklyn Bridge Station; The Wanamaker and Clinton Hall Buildings at Astor Place; Hotel Royal at 14th Street; the Florence Apartments at 18th Street;



BASEMENT STORY OF THE MERCANTILE BUILDING OPENING INTO THE 23D STREET STATION AT THE S. W. CORNER OF 4TH AVE. AND 23D STREET.

the Mercantile and Metropolitan Building, at 23rd Street; The Grand Central Railroad Station and Belmont Hotel at Grand Central; and the Times Building and Knickerbocker Hotel at 42nd Broadway.

The tunnel stations are local stations. Only two tracks pass through them. One ticket-room serves for both the up- and down-town platforms. It is located just below the street surface, and is accessible by a short flight of steps. Owing to the extreme depth of the train platforms below the surface they are reached by a pair of elevators, which operate between the ticket-room level and a transverse passageway below, crossing over and serving both train platforms. Both platforms and the tracks are spanned by a large brick masonry arched roof. The sidewalls and floors are finished in the usual manner.

The elevated stations consist of two platforms, one on each side of the street. On each platform a station house containing the waiting and toilet rooms, and ticket-booths is constructed. It is built of steel framing sheathed inside with oak and outside with copper.

In constructing the stations there are two operations. First: building the exterior sidewalls, floors and roofs. Second: constructing the interior or finishing walls, floors, and ceilings; erecting the stairways and toilet room fittings; and equipping the station with the ticket booths, doors, railings, gates and lighting fixtures. The exterior of the station is constructed of steel sidewall and roof beams spaced about five feet apart and filled in between with concrete arches, the whole supported on a foundation floor of concrete. Over the platforms the roof is supported by cast iron columns fifteen feet apart. Those columns have ornamental bases and caps. Where the roof comes under the sidewalk areas the concrete arches are omitted and the glass vault light construction substituted. To prevent the ground water from finding its way from the outside into the station, a waterproof envelope, consisting of several layers of felt and asphalt, and protected by an outer shell of masonry, surrounds the whole structure — under the floor, outside of the sidewalls, and over the roof (except the vault light areas).

After the station has been constructed in the manner just described it is lined on the inside with the finishing walls, floors and ceiling. To reduce the condensation to a minimum, however, and thereby make the stations as damp-proof as possible, a two inch air space is left between the inner and outer walls and ceiling. Ventilation openings are provided through these walls and ceilings to induce, as much as possible, a circulation of air in the air space. And further, in particularly wet ground, the air spaces are connected with pipe drains so that any water which may leak through the outer water proofing may be caught and carried away.

The finish work has been executed from plans prepared by Messrs. Heins & La Farge, the consulting Architects to the Commission. The scope of their work included all the details of finishing and equipping the stations, thereby insuring harmonious results. Though the stations are numerous, they have succeeded admirably in giving some individuality to each one. This variation in design is pleasing, and besides it serves a useful purpose. Passengers may recognize their stations at a glance as readily as if they could see the surrounding buildings in the street. The architectural treatment is rendered mainly on the side walls, though the ceilings are also finished in an ornamental manner. To accomplish the large variation in design necessary, the stations have been divided into several design groups. All the stations in each group are rendered alike in line and character of ornamental treatment, but the color scheme of each station in the group differs from all the others of the same group.

The finishing sidewall rests on the floor foundation concrete and extends to the ceiling. It is set out two inches from the back wall to provide the required air space. The base of the wall is constructed of hard buff-colored Norman brick to a height of about $2\frac{1}{2}$ feet above the finish floor. This forms a durable wainscot extending around the whole perimeter of the station. Above the Norman brick to the ceiling or vault light line the wall is constructed of common brick a single brick thick. At about 8 or 9 feet above the floor level an ornamental

faience or terra cotta cornice is set into the wall. The face of the common brick wall is set back about $1\frac{1}{4}''$ from the wainscot line to allow for a tile finish between the wainscot and cornice and a Keene Cement finish above the cornice. The thickness of the wall including the finish is about five inches and it is securely anchored to the exterior wall of the station. The Norman brick wainscot, with a few exceptions, is common to all designs. The variation in the designs occur in the cornice and in the rendering of the tile work between the cornice and wainscot. The cornices are modeled in low relief with different decorative motives for each group. To give greater variety and to fit in with the several color schemes the material is furnished in one, two or three colors. Opposite the platform columns or at intervals of 15 feet, the cornice is broken by ornamental plaques containing the symbol or number of the station. The plaques are sometimes enriched with special designs suggested by local associations. The Beaver at Astor Place; the Caravel at Columbus Circle; and the Columbia University Arms at the Columbia University Station are examples of this. The wall space between the cornice and wainscot is mostly covered with $3'' \times 6''$ white glass or glazed tile. The enrichment of the surface varies with each station. Narrow mosaic bands in single colors, pilasters and friezes in ornate designs of several colors, and cream colored glass tile are employed in the decorative compositions. In some stations pilasters, located under the cornice plaques, separate the wall into panels about 15 feet long. The panels are finished off with borders of mosaic and cream colored tile. On other stations the pilaster effect is omitted, the wall only being finished at the top and bottom with bands of cream glass and mosaic. The mosaic colors harmonize with those of the faience and terra-cotta. The whole effect is pleasing and forms a most comprehensive scheme of ornamentation. In addition to this and the station numbers or symbols which occur so frequently along the cornice line, striking name tablets are worked into the decorative scheme. There are usually three of these on each platform, they are constructed of mosaic and form a central motive in the wall panels. The color of the body of

the tablet or background for the lettering is in strong contrast with the station color scheme, and its ornamentation is very simple, so that the tablet with its significant lettering readily catches the eye. The treatment of the walls of the tunnel opposite the island platforms is somewhat different. Glass and mosaics are used but they are applied directly to the concrete of the tunnel walls, the flanges of the I-beam columns being exposed to view.

The floors of all stations are alike. They are constructed of concrete with a granolithic finish. The surface is blocked out into three foot squares. The floor consists of two layers. A foundation of broken stone concrete two inches thick, and a one inch finishing layer of Portland cement and white sand. This forms a durable floor of a light gray color. A small curve of one inch radius is formed in the floor at its junction with the sidewall, providing a sanitary cover around the whole platform, and thereby avoiding a place for dirt to collect in. The floor surface is usually graded to drain to several selected points, where catch basins are located connecting with drains leading to the sewer. If desired the platform surface can be thoroughly washed down with hose — water connections have been provided on each platform for this purpose.

There are two types of ceilings, finished in white Keene Cement. One is arched and the other flat, both are suspended and provided with a two inch air space under the roof concrete. The former construction is used when the head-room permits the roof concrete to be built in an arched form, and set up above the roof beam flanges; where this cannot be done the latter construction is used. To construct the arched ceiling, one inch channel irons are bent to conform to the concrete arch and supported on the roof beam flanges. These irons are spaced about 12 inches apart and form ribs upon which galvanized iron wire lath is fastened with clips. Upon the latter surface three coats of plaster are applied, scratch and brown coats of Portland cement mortar and a finish coat of White Keene cement. The girder and beam flanges running over the platform columns are covered with wide ornamental plaster molding which sepa-

rates the ceiling into panels. All other flanges remain exposed. In the flat ceilings, however, all steel and concrete in the roof of the structure is concealed. The irons supporting the wire laths are clipped under the flanges of the beams and girders. The plaster coats are applied in an even surface over the whole area. Wide ornamental molding running from column to column as before, form ceiling panels which are further decorated with finer moldings and rosettes. In addition to minimizing the condensation, the air spaces back of the walls and ceilings are utilized by the electricians to conceal all the lighting conduits.

More than the customary toilet room provisions have been made. In addition to the usual outfit, each toilet room contains a pay closet, admission to which is controlled by a nickel-in-the-slot lock. This room is fitted out with a basin, mirror, soap and towels. The toilet room fixtures have all been designed especially for the Subway work. They are made in porcelain, and finished with dull nickel fittings. None of the soil, vent or water pipes are exposed, but in order that they may be easily accessible for repairs they are run in wall spaces back of the wainscot. The floors are of concrete similar to the regular platform floors. The walls are finished with a wainscot 6 feet high, and above this in White Keene cement. In many cases the ceilings are of glass vault light construction, otherwise they are finished in Keene cement. The partitions are finished to the same heights as the wainscot and are supported and fastened with dull nickel fittings. The wainscot and partitions have been furnished in red slate or marble. A small electric fan in each room produces the necessary ventilation. The only heat provided in the stations is furnished by electric heaters installed in the toilet rooms and ticket booths. All the woodwork is of oak finished in the natural color. Most of the stations are below the sewer levels, so that it has been necessary to raise the sewage to the sewers. Automatic air ejectors are employed for this purpose. The air for operating them is furnished by a small compressor plant installed in each station.

The ticket booths are constructed of oak finished in the natural color. They are ornate in design and are finished with

bronze window grilles and fittings. The railings are constructed of wrought iron pipe and special cast work The stairway grilles and exit gates are of simple design in wrought iron. At the stations all exposed metal work has received a finishing coat of paint. The column bases and all railings, grilles and gates have been painted a dark green color, all other metal with white enamel paint.

The stairways are constructed of concrete reinforced with twisted steel rods. This type of construction was best adapted to the conditions existing in the Subway, and was most effective and economical in design. The treads and landings are covered with lead safety treads. The stairwell openings at the street surface are usually covered and protected by kiosks constructed of cast iron and wire glass. These structures are ornamental and are designed to occupy as little of the street surface as possible.

All stations are equipped with heavy oak seats of special design. Electric clocks on each platform indicate the correct time. The ticket-booths contain a fire alarm and telephone service. Should a passenger fall off a station platform upon the tracks, by pushing a button set in a conspicuous place signals can be set in the face of, and so stop, all approaching trains.

The numerous details of the station finishing work are executed by different sub-contractors. Generally the contracts have been let upon a percentage or unit basis. This has been done because in most cases it was necessary to obtain contracts and proceed with the manufacture of the materials needed, and the execution of the work, before all the plans were completed. The plan has proved to be satisfactory. Approximately one and three quarter million dollars will be expended upon the finishing work.

In conclusion I desire to express my obligations to Mr. Parsons, Chief Engineer to the Commission, for permitting me to make use of the matter employed in the preparation of this article.

PROBLEMS OF AN ARCHITECT IN THE REMODELING OF NEW YORK CITY.

BY JOHN A. GADE, NEW YORK CITY.

THE most frequent problem presented to-day to the architect in New York City, is the remodeling of one of the endless rows of dwelling houses built from 1850 to 1890. Miles upon miles of these were erected directly after the Civil War, with a two to three inch ashlar facing (becoming 4″ in later years) of what now is popularly termed "brownstone." It is a brown laminated sandstone, the first such to be quarried in this country, and came principally from Portland, Connecticut. Though not subject to direct disintegration, frost affects it, moisture penetrates the laminations in the stone, and its outer surfaces and angles very soon begin to peel and scale off in so decided and rapid a manner, that architects cannot consider its use for exterior surfaces. Added to the weakness of the cementing materials in the stone, came also its faulty laying, the courses almost invariably being set on edge, instead of on their natural bed. Its disintegration led, after a number of years, to the establishment of about as many stone renovating and stone repairing companies in New York City as offices of new and better quarries. Not a summer would pass without the scaffoldings of artificial stone companies hanging, at least one, in front of every block, the masons chipping off the loose surfaces and skillfully applying new coatings of ground brownstone and Rosindale cement, colored to match as accurately as possible with brown umber and lampblack, and finally bleached to an exact resemblance to the adjoining surfaces.

Besides the "brownstone" fronts, a number were built out of Potsdam stone (also a sandstone, but of more durable type), and of Lee and Tuckahoe marble.

Almost all their elevations were miserable, both in proportions and detail. The greater number were as similar one to another, as peas in a pod, and designed directly by the builder

or contractor. The carving and ornamentation was of the heavy, meaningless, elaborate type, characteristic of all the architecture and furniture of the period. The best that at present can be done with it is to give it an entirely clean shave. This poverty in the facades is not to be wondered at, for it was the outcome of merely speculative building operations, and the purchasers of the houses bought them with less individual fastidiousness than they would have displayed in the purchase of a hat.

The plans are similarly identical, this to a certain extent being occasioned by the houses being more nearly of uniform width than at present, varying merely from 16 to 30 feet, perhaps, instead of from 16 to 100. It is quite interesting to note the origin of their structure. One can still find examples of this in a few of the older specimens preceding the brownstone invasion, lying in the old Greenwich village, stretching west of the Jefferson Market Courthouse and on the old Cherry Hill, around Franklin Square, and the New York end of the Brooklyn Bridge.

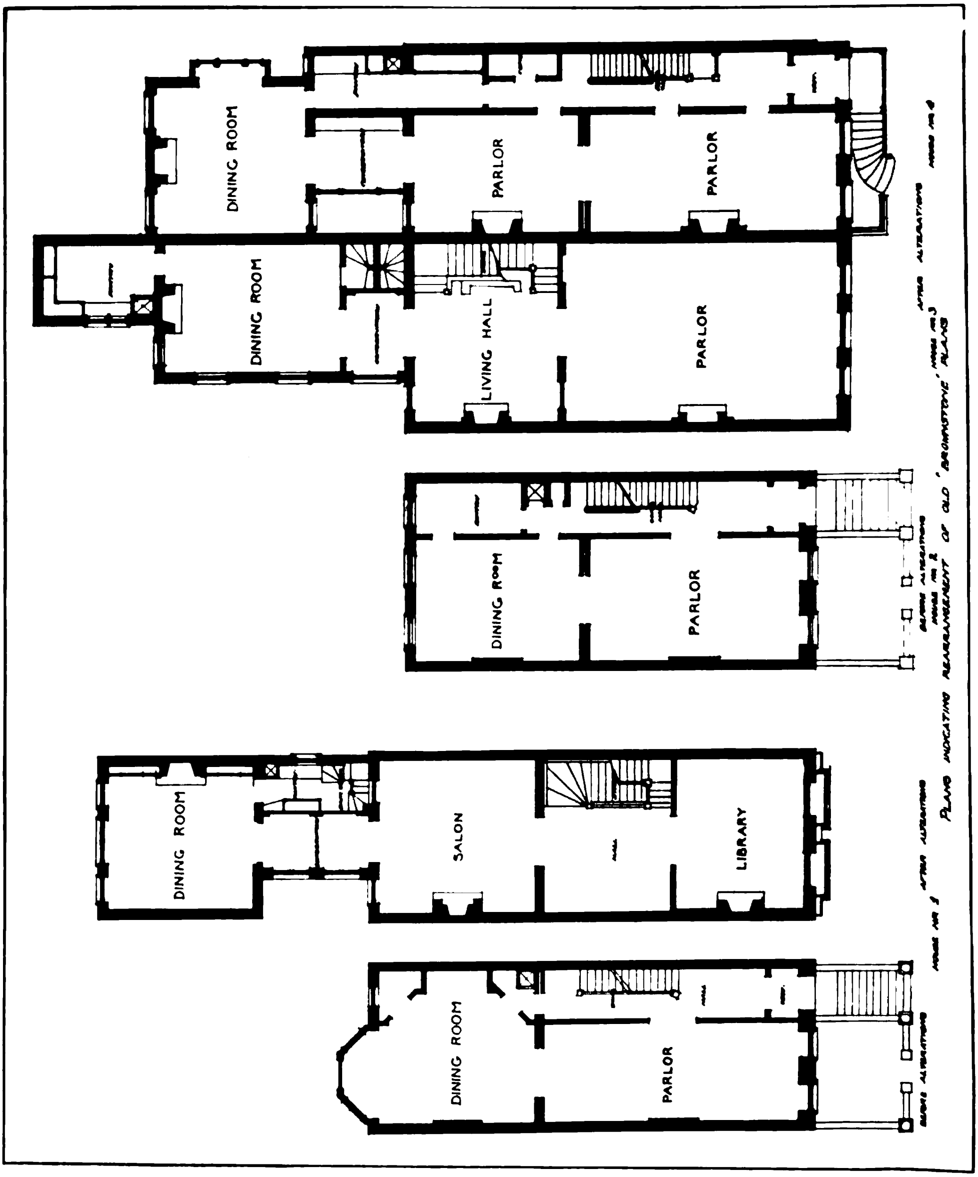
In these houses there are no cellars at all, the basement was the storehouse, and as it was not used for living purposes, could be built at a sufficiently low level to enable the family to enter the ground floor of the house by three or four easy steps. The house was thus originally what is now called an "English basement" in opposition to the "American basement," entered either on the same level as the sidewalk, or by going down a few steps.

The necessity for more storeroom, greater conveniences, and the employment of the basement for servant's quarters and service, raised it, so as to admit more light and air. Hence the high stoop. Further, the whole house was stretched, becoming in the larger examples, as much as sixty feet deep, and allowing the centre of the house on the bedroom floors, wardrobes, closets and lavatories; on the ground floor, between the long, narrow parlor in front and dining-room in the rear, there arose a funereal library. The hall rooms, in the rear of the bedroom floors, became bathrooms. In the earlier houses, toilet conveniences had been in a separate house in the back yard, and of bathing conveniences there had been none.

Modern plumbing dates from some time immediately preceding the Civil War, — in fact the first definite and effective regulations are scarcely older than 1880. Back-air piping and the use of extra-heavy piping is only about twenty-five years old. Modern plumbing came from England. An Englishman, J. J. Hellyer, was the father of it, and the first to employ to it truly scientific and hydraulic methods. Merely pan closets and tin tubs had been in use before his time. He invented the hopper water-closet, which is the prototype of every modern one, and he commenced the wide and extensive manufacture of all kinds of fixtures and plumbing goods which he shipped to the United States (mainly to Boston). Their immense sanitary value, and their comfort, were instantly realized and they were placed in every newly erected dwelling house, piping and fixtures always carefully enclosed and ceiled where defects could not be reached, but dust might accumulate.

In connection with the foundations of the many brownstone houses, it is of interest to notice the old topography of the city. One of the great difficulties New York architects and engineers have to contend with, is the careless manner in which underground watercourses were cared for when the city first started extensively extending north of City Hall. The citizens, instead of making provisions for the subsurface streams and swamps and lakes, by building proper conduits draining them off to the Hudson and East rivers, merely filled them in. The result is, that there are at present, under the city at various points, good watercourses, which have only partially been taken care of, as the occasion and necessity have arisen. In cases where diverting or draining becomes too expensive, piling is resorted to, or one is obliged to dig to such surface as one deems solid. In two of the last alterations I have made, I was forced in one case to pile, in the other to go down with my concrete footings thirty-two feet below the level of the sidewalk.

The result of the insecure bottom below the "brownstone" foundations has been that the greater portion of the houses have settled. Hardly two rooms have the same dimensions at



PLANS INDICATING REARRANGEMENT OF OLD 'BROWNSTONE' PLANS

opposite ends of the room, nor do ceilings in the front and rear of the same story measure the same height. These inaccuracies were partially due, it is true, to the fact that party walls were rarely built plumb, but often 4″–6″ out. The old survey records are so miserable that architects and engineers have largely to depend upon private ones. The party walls were naturally inventions of the speculative builder.

The basements had 24″ stone walls, the ashlar in this story projecting 4″ in front of the face above, 12″ of brickwork backed it, except in the rear, where the top story would generally be cut down to 8″. Internally the walls would be furred with studs to give the requisite depth for the folding blinds to lay back flat. The brickwork of the walls themselves discloses poor bricks, miserably laid, and cement far inferior to good, modern brands.

The stories were approximately built of the following dimensions: Cellar 7′–0°; basement 8′–0°; first floor 13′–0°; second floor 11′–6°; third floor 11′–0″; fourth floor 9′–0.

The framing was universally 2″ × 10″ beams, while we at present use a minimum thickness of 3″.

In only a few points can we look back with regret to the workmanship of these houses. One so often hears inexperienced owners or house-hunters of to-day sigh at their own remarks, "that we no longer build as they used to," "that we employ poorer materials and worse labor." This is nonsense. We *do* build as well, at least capable and conscientious architects and contractors do — except where the client, righteously half-maddened by strikes, endeavors to hurry the work beyond the point where it can be executed to its best advantage. The houses built "on spec" are naturally exceptions to my denial.

The cast iron ornamentation used in the brownstone houses, reached a very high grade of perfection. One has merely to compare some of the lumbersome old balustrades enclosing the stoops, with some of the slighter modern ones, to observe the difference in their casting. The old show a far superior knowledge of casting, are sharper and cleaner cut, though their design may be ugly and their details at present clogged with successive coats from unskilled painters' brushes.

TYPICAL BLOCK BEFORE ALTERATIONS.

In regard to the interior wood, the sigh for the old is certainly more justified. Take for instance some of the magnificent mahogany doors, with wonderfully grained and polished panels, some of them 10′ high and 3′ broad. Their wood grew in the lowlands and swamps of San Domingo, where there also naturally was a limited stock. Chippendale was the first to realize its value, not because of its beauty but because of its strength, which enabled him to make durable furniture of the delicate proportions he desired. The first exportation thus went to England — New Yorkers procured some of the last of the best stock. The old doors and panels were veneered with slabs from $\frac{3}{8}''-\frac{1}{2}''$ and more thick, while our modern ones seldom have a veneer more than from $\frac{1}{32}'' - \frac{3}{16}''$ thick, and the greater portion of them are made of baywood, though delivered as mahogany. In the old ones, the wood for trimming the rooms, was first selected, as it would be for violins, after five to ten years' standing and absolute drying. Now we force our drying, we specify "kiln-drying," meaning a rapid, injurious closing of the pores, generally accomplished in two to three weeks' time; finally we heat our houses in a manner, and to a degree, far above the resisting power of any woodwork, whatever process it may previously have experienced.

The moldings and ornamentation of much of the interior trim in the "brownstone" houses were as offensive as those of the exterior stone-work, but the trim was, when finished, better put together by the carpenter of the old house than by the carpenter of the new. (I am speaking of carpenter and not cabinet work.) The reason lies in the fact that the mechanic in old days not only carved the wood but also fitted it, now he receives it machine carved and machine fitted and merely tacks it together, with no leaway or fitting left for careful adjustment. Wood being so much cheaper likewise caused cross-sections to be made of much more generous proportions. It interested me to notice that some houses (much earlier than of the type in question) had wooden window sills 5″ × 6″ thick, now we seldom make them more than 2″.

A hundred years from to-day one will probably hunt with

HOUSE NO. 1 AFTER ALTERATIONS.

difficulty in the fashionable resident district of New York City for a single one of the old brownstone fronts. They will all either have been torn down or altered. The reasons for their disappearance are the demand for more room, better lighting, sufficient heating, entirely new plumbing, and interior arrangements more in accord with modern social conditions.

The first step, incurring the least interior rearrangement for the procuring of more room, was the addition to the old house of a one-, two-, or three-story extension, giving laundry, servants' toilet, pantry, backstair and ballroom. This extension has, during the last twenty years, been constantly tacked on to the backs of New York houses, to a greater or less height.

The second step was radical. The exterior windows were rebuilt and the rooms replanned so as to admit better light everywhere, all the central closets and lavatories were exterminated, and new ones planned, well lighted by large skylights or lightshafts, the dark staircases were replanned so as to admit direct light on some of the landings, and the small purple and amber headlights were changed to lights four to five times their size, and of the most practical brilliancy. Electricity replaced, or was coupled, with gas. Steam and hot-water plants were introduced. Furnace flues and pipes of decent, efficient sizes substituted the old ducts. Completely new "open" plumbing was put in, and living rooms and bedrooms planned and detailed so as to look comfortable, cheerful and livable, instead of sepulchral, depressing and intolerable.

The exteriors were either entirely rebuilt, the new front much to the detriment of the streets, being brought out to the building line, and erected in a buff or blue Indiana Limestone, Milford granite, marble, Potsdam stone or brick — with or without stone trimmings; or the exteriors were recut and retrimmed and the main entrance of the house lowered from the ground floor to the basement, at whatever distance this might be below the curb level, the stoop thus entirely being done away with. In a few instances there may, externally, merely have been a "renovation," the changes limiting themselves to the replanning of the house in connection with a large extension extending either the total width of the lot or merely a portion of it.

As to the designs of the exteriors: the first Colonial epidemic has been followed by every possible style,—by Gothic arches, every period of Italian and French Renaissance, by Classic detail, and the very latest development of Beaux-Arts Cartouche and

HOUSE NO. 2 BEFORE ALTERATIONS. NOS. 3 AND 4 AFTER ALTERATIONS.

mud ornament. It is by accident and not by intention that two facades in a block hang together.

But out of all this change, this endless wearing away and rebuilding by the current of architectural thought, limited by necessity to such narrow channels, what deductions can one draw?

These.

Decided ideas and interest have been awakened in the owner of the house, as to its interior and exterior appearance. Modern plumbing is, without exception, insisted on by the owner, and enforced by the law, sunlight is admitted in our home and city life, as well as in our out-of-door and country life. We can without freezing or huddling next to heating flues and fireplaces remain comfortable in all portions of the house and we can tell, as we turn the corner of our block, what house-front represents our own individual taste, instead of fumbling hopelessly with our latchkey in our neighbor's door taking it for its twin brother next door. And the general interior arrangement shows the result of our study and earnest striving in this portion of the world to procure in architecture more logical expression of the artistic aspirations and practical requirements of our social conditions.

The greatest Norwegian artist answered me after visiting this country, when I asked him what impression the great American cities had made on him: Philadelphia — a red symphony, Boston — a yellow simplicity, New York — a brown blotch.

Impressions may be counteracted, realities cannot.

THE HAVANA POLICE SIGNAL SYSTEM.

By H. DuB. B. Moore.

With the lowering of the Spanish flag from above the walls of Morro Castle on December 10th, '98, there closed an interesting epoch in the history of the island of Cuba. For nearly four hundred years Spain had occupied the island and during that time she had done much, and yet left much undone, which contributed directly to its welfare.

But with the evacuation of the island by the Spanish troops died the last remnant of Spanish civil government and it necessarily became one of the chief cares of the American occupation to create efficient governmental machinery to supply its place.

The municipalities were among the first to receive attention, and the city counsel of Havana was speedily reconstructed on modified Spanish lines. With the reconstruction of the counsel, logically came that of the various municipal departments and, as to be expected in a city so recently left without a government, the police received a full share of thoughtful consideration. With this end in view, a gentleman of great ability who had been connected with the New York police for many years, was given the task of forming an efficient and adequate force. At first the organization closely followed its American model, but it has since been modified to some extent to meet the local conditions.

The City is divided into twelve (12) precincts, including the town of Reglan which lies across the bay much in the manner that East Boston does from Boston. Each precinct has a captain, four lieutenants, who perform the duties entrusted to the sergeants of the New York force, and sergeants who correspond to the New York "roundsmen." The number of men attached to each station varies with the size of the precinct. The "two-platoon" system is in use, each man having so many hours on patrol, so many in reserve in the station house, and so many hours off duty each day.

The whole force is directed from the police headquarters, a large, centrally located building known as "la Jefactura," where are situated the offices of the chief of police, adjutant, paymaster, and other general officials.

The following table will give some idea of the size and distribution of the Havana police.

Name of Precinct.	No. of Precinct.	Captains.	Lieutenants.	Sergeants.	Men.	Remarks.
	1st	1	4	4	74	
	2nd	1	4	4	72	
	3d	1	4	4	79	
	4th	1	4	4	55	
	5th	1	4	4	55	
	6th	1	4	4	61	
	7th	1	4	4	51	
Pilar	8th	1	4	4	56	
Vedado	9th	1	4	4	54	
Jesus del Monte	10th	1	4	4	64	
Cerro	11th	1	4	4	78	
Regla	12th	1	2	3	46	
Jefactura	—	3	3	—	—	Police Headquarters.
Vivac	—	1	3	1	78	The Vivac is the city prison and is garrisoned by rural guards furnished by the state but paid by the city and officered from the police.
Total	—	16	52	48	745	Not including Vivac men but including officers.

With the reorganization of the police came the question of the advisability of installing a signal system for the use of the force. The points to be considered were discussed at some length and finally resolved themselves somewhat as follows: (a) That the installation of any system entailed a considerable outlay of money for a city impoverished by a long continued war; and (b), that such an installation necessitated an annual appropriation for its maintenance. On the other hand its advantages were such as could not readily be overlooked. Such a system gave the station house a constant control over the men on their beats. By a regulation requiring them to report from the

signal boxes on their beats every half hour, the lieutenant on duty at the station could, by means of the telephone, give the men any necessary instructions. The men in like manner could call up the station at any time for advice or orders.

Another important feature was that it prevented the men from leaving their posts thus lightening the duties of the sergeants on patrol duty and at the same time it protected the men from false charges of being off post. Furthermore it enabled the policeman in case of an arrest to call the patrol wagon to take the prisoner to the station and obviated the necessity of his leaving his post unprotected for an uncertain length of time. This ability to communicate with his station at any time would also enable each man to effectively cover a much larger territory, and thus an unnecessary increase in the number of men could be avoided. Another idea which presented itself was that the system could be used as an auxiliary for the fire department. At present the fire department depends upon a number of telephones scattered in private houses and stores throughout the city. These telephones are connected directly with fire headquarters, but the service and maintenance are wretched.

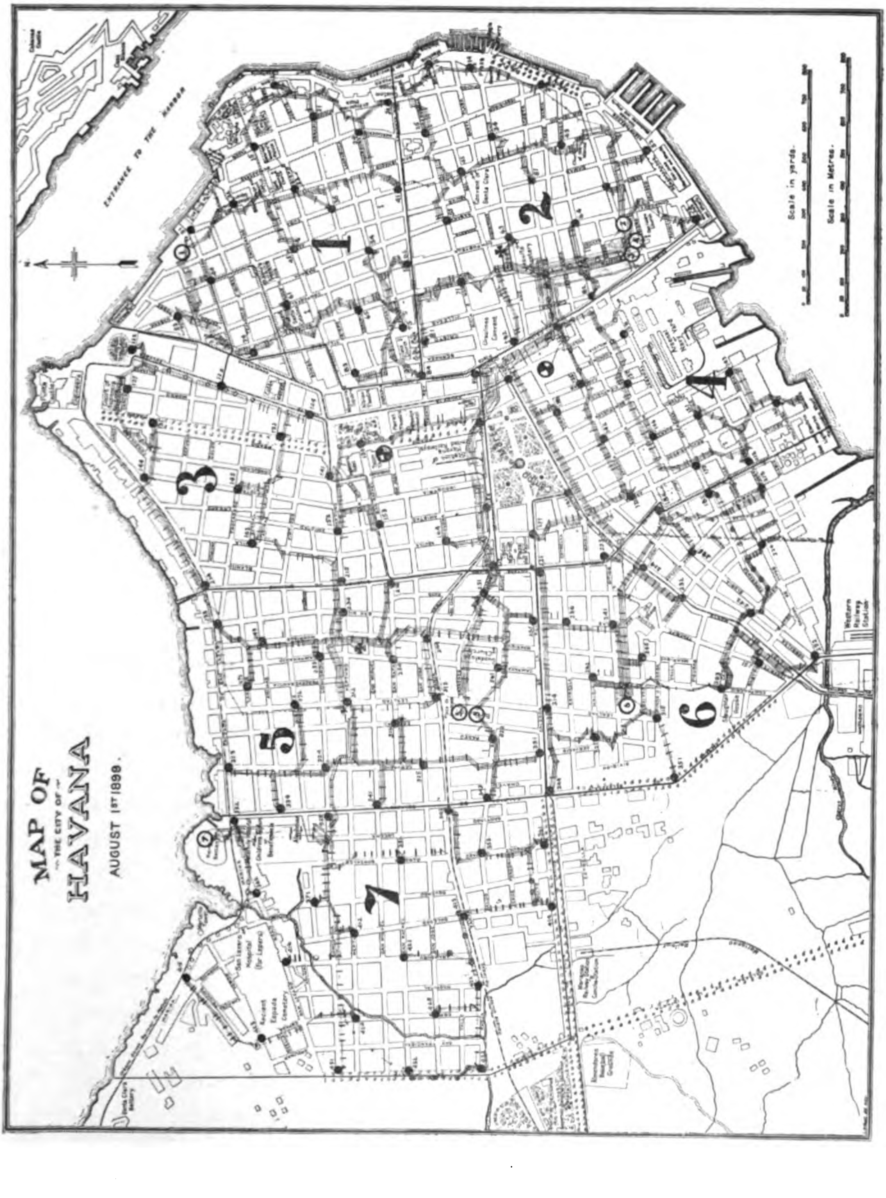
It was decided by the city upon consideration that the advantages more than counterbalanced the additional expense entailed. Especially as after the initial cost of the system was met, its maintenance would be far less than the salary of the additional men otherwise necessary.

The system decided upon was what is known as the "Gamewell System" which is employed in a great majority of Ameri-

Symbols explanatory of diagram on opposite page:

1 in circle — Stations marked thus with proper no. of precinct.
J in circle — Jefactura marked thus.
× in circle — Fire stations marked thus.

×	Emergency hospitals marked thus.
●	Boxes marked thus.
| | | |	Fixtures " "
1 2 3 4 5	Boxes numbered thus.
	Precincts numbered in large numerals.
———	Precinct boundaries marked thus.


MAP OF
THE CITY OF
HAVANA
AUGUST 1ST 1899.
ENTRANCE TO THE HARBOR
Scale in yards.
Scale in Metres.
Western Railway Station

can cities, and has been in successful operation for many years. In the "Gamewell System" each precinct is a complete unit, the station house being the point to which all lines converge.

The boxes are placed throughout the precinct, at least one, on each patrolman's beat. Generally speaking one box can be used by two men by placing it at the intersection of two beats. They are made of heavy cast iron and contain a lighter cast iron interior box. The outer box or shell serves as a protection from the weather and against mechanical injury. Each box contains two absolutely distinct circuits, one a telegraph and the other a telephone circuit. On opening the outer door, to which every policeman has a key, there is disclosed to view the door of the inner box carrying a dial plate with seven signals. In the Havana installation these were arranged as follows:—

1. Carro (patrol wagon).
2. Ambulancea (Ambulance).
3. Teléfono (Telephone).
4. Incendio (Fire).
5. Reserva (Reserve).
6. Reporté (Report).
7. Official (Official).

Below the dial plate is a small pointer set on the signal "Carro" whose position can be shifted to cover any of the above signals. Below this again is a handle. Now the operation the policeman must go through to send a signal, is merely to set the pointer upon the desired call and pull the handle down as far as it will go. He then releases the handle which together with the pointer returns to its original position.

All this concerns only the telegraphic circuit which, roughly speaking, operates as follows: Each twelve or fifteen boxes in the precinct constitute a circuit and each box on the circuit is connected up in series with the rest. By an automatic device, closing the outer door short circuits the box throwing it off the line. The line itself is supplied by some thirty closed circuit gravity cells or, in the case of a large city, from a central storage battery charged from any available source of supply. In Havana each precinct had its own battery of 6″ × 8″ gravity cells.

Opening the outer door throws that particular box on the circuit. The signal is then sent by means of what is known as a "break wheel," — a small wheel containing a number of notches. Pressing against the edge of this wheel, by means of an adjustable spring, is a smaller wheel attached to a small lever. At the other end of the lever-arm is a platinum contact. Pulling

the handle winds the clockwork mechanism and causes the "break-wheel" to revolve. As the wheel revolves the notches allow the smaller wheel to drop and break the circuit by separating the platinum contacts at the other end of the lever-arm. This breaking of the circuit causes an automatic register in the

station-house to record, in ink, on a paper tape, not only the signal but the number of the box. A recording clock in the station is operated at the same time stamping on the tape the time and date of the signal.

Inside the box and in series with the circuit is a small electric bell which repeats the signal, so that the policeman knows the box is working satisfactorily. This bell can be operated from the station by means of a push button which breaks the circuit and is used to notify the patrolman he is wanted at the telephone. It has yet another use. Should a policeman on opening his box find his bell ringing he knows at once another signal is being sent. This is so, because all the boxes are in series and opening this door throws his box on the line. If the line is in use, his bell being in series with it, will repeat whatever signal is being sent. When this occurs the policeman must wait until the signal is finished, otherwise the two signals will conflict.

The signals used are of the dot and dash variety, and the numbers of the boxes are shown by dots.

1. Carro ———
2. Ambulancia ——— –
3. Teléfono ——— – –
4. Incendio ——— – – –
5. Reserva ——— – – – –
6. Reporté – – – – –
7. Official – – – – – –

For example, suppose the policeman at box No. 143 wants the ambulance; the signal received at the station would be:

——— –	–	– – – –	– – –
Ambulancia	1	4	3

The first five signals on the dial plate of the box are what are known as emergency signals. If the register receives any one of these it is so arranged as to automatically throw a drop, operating a bell which rings continuously until the drop is replaced.

The object of this is to notify the lieutenant in charge of the station that a signal has been received that requires his immedi-

ate attention. The "reporté" and "official" signals, the latter being used by the sergeants in reporting, can be checked up daily and therefore do not require his attention.

At the station end of the line the apparatus consists of a desk on which all the instruments are placed. Each telegraph circuit comes to a relay. The relays are of the double contact telegraph type with platinum contacts, the register, time-stamp clock, emergency bell, drops, etc., all being operated on secondary circuits equipped with open circuit batteries. The register is provided with a separate pen for each telegraph circuit so that signals can be received from boxes on the various circuits at the same time without interference. Each circuit is also provided with its own drop. There is also a transmitter dial by means of which the number of any box can be transmitted to an indicator located in the stable where the patrol wagon is kept.

But to return to the interior door of the street box. Below the telegraphic apparatus is a mouth piece screwed into a hole in the face of the door and to the right a hook on which hangs a receiver. There is no magneto. When the policeman wishes to use the telephone he places the pointer on the third signal, pulls the handle and places the receiver to his ear. At the station the register records the signal and time, throws the drop, and the bell calls the officer in charge to the desk.

The arrangement of the telephone circuit is very different from that of the automatic telegraph. A metalic circuit is used and the instruments all placed in parallel. Removing the receiver from the hook throws in the dry battery, with which every box is provided, and throws the instrument on the line. At the station house the instrument desk is provided with a desk telephone which can be thrown on any line by means of a row of switches.

There remains but one feature more in this summing up of the most important points of the system, and that is the "Citizen Key Attachment." Each outer door of the boxes contains a keyhole marked Citizen's Key. When a key is inserted in this lock it passes through the outer door and enters a socket cut in the base of handle on the inner door. When the key is

turned it pulls down the handle in the manner before described. This lock is a trap lock and once the key has been turned it cannot be withdrawn without unlocking the outer door. As the dial pointer always returns after use to the first position, using the citizen's key invariably sends in a call for the patrol wagon. Some fifty keys are distributed among the responsible residents

of each precinct, and in the absence of a policeman serve as a valuable aid in obtaining police assistance.

In the installation of the apparatus in the City of Havana there were but few changes made and those of an entirely non-essential character, such as casting the outer doors of the boxes with Span-

ish inscriptions, etc. The entire equipment to all purposes was the same as that used by cities in the United States.

The local physical conditions met with presented no great difficulty. Havana, except in the poorest outlying districts, contains no wooden houses, the material exclusively used for building being coral rock. This coral rock is a soft cream white stone capable of being sawed or hewed into shape with an adz. It has the property of hardening slowly on exposure to the air. The exterior of the houses are plastered and painted with water colors to suit the owner, generally sky blue with white trimmings, although light yellow with red trimmings is also a favorite. The roofs in the better part of the city are flat and tiled, with the walls extending far enough upward to form a heavy parapet, their thickness at the top being some two feet or more. Besides this type of roof there is a certain percentage of houses covered with either the Spanish or French red tiles, but the greater majority, by far, are of the above class.

The streets in the old part of the city are extremely narrow, being barely wide enough for two vehicles to pass. This has resulted in an ordinance that traffic shall move but one way — up one street and down on the next parallel one. In this section the sidewalks do not average more than two or three feet in width.

These conditions precluded the use of poles to any extent, and as there are no existing underground conduits, the situation plainly indicated roof fixtures.

Where but three or four wires were to be carried the fixture consisted of a 2″ × 4″ cross section of yellow pine upright pointed at the upper end. To this a cross arm was fastened by means of a 5″ × $\frac{1}{2}$″ machine bolt. The cross arms were of a special design slightly heavier than the usual standard four pin cross arm, mineral painted and bored for 1$\frac{1}{2}$″ diam. pins. The pins were of the best oak and also mineral painted.

Standard, deep groove, glass insulators were used. These fixtures were fastened in place by 15 six inch wire nails driven into the walls of the buildings. The majority of the fixtures were of this class, but where more than five lines were carried a heavier

fixture consisting of a 3″ × 4″ cross section upright, carrying two 4-pin cross arms was substituted. These latter were held in position by two iron clamps cemented into the walls. Smaller fixtures were treated in similar fashion whenever the walls were too soft to give the nails sufficient hold.

Poles were necessary in some of the newer portions of the city, and for a four wire line consisted of a 4″ × 4″ × 30′ pole with a four pin bolted cross arm. For one line carrying twenty-two wires, 8″ × 8″ × 40′ poles were used with three 8-pin cross arms.

Number 8 galvanized iron wire was used for guying all fixtures and two twisted wires for the light poles.

The line itself was constructed of No. 12 B. & S. hard drawn, weather-proofed copper wire and all joints were of the three wire type and soldered.

The total number of street boxes installed was 142, these being divided among the precincts as follows:

1st	Precinct	has	21	boxes.
2nd	"	"	19	"
3d	"	"	20	"
4th	"	"	17	"
5th	"	"	23	"
6th	"	"	21	"
7th	"	"	21	"

These were placed at the corners of the streets upon the walls of the abutting buildings. A heavy "back board" cut in the shape of the box and 2″ thick was first nailed with 6″ wire nails to the wall at the desired height, and to this the box was secured by means of three 2″ wood screws. The four wires were brought down from the nearest fixture to a "dead end arm" of yellow pine 2′ 6″ × 4″ × 2″ thick, planed, its outer edges beveled, and carrying four No. 3 porcelain insulators equally spaced. This dead arm was nailed directly above the box. From this point the wires were carried to the interior connections of the box through a ½″ galvanized iron pipe extending from the box upward some eight feet. The wire

used to make this connection between the "dead end arm" and the box was No. 12 B. & S. soft drawn, weather-proofed copper wire. As each box is provided with a lightning arrestor a ground was necessary. In this case the grounds consisted of a $\frac{1}{2}''$ iron pipe six feet long to which was soldered a No. 10 B. & S. soft drawn bare copper wire. This was carried into the box through a $\frac{1}{2}''$ galvanized iron pipe extending downward from the box to $3''$ below the pavement.

The lines entering the stations went to racks fastened to the exterior walls and thence through lightning arrestors into the building by means of $\frac{1}{2}''$ porcelain tubes. All the interior wire-ing of the stations was done with No. 16 damp proof office wire, and all lines entering the instrument desk passed through $\frac{1}{2}$ ampere fuses. The interior of the desk was also equipped with other lightning arrestors.

In addition to the regular "Gamewell System" an auxiliary telephone system was installed. A telephone exchange of thirty lines was placed in the Jefactura with wires to seven station houses, to the Vivas, to the office of the mayor, fire department, emergency hospital, etc.

All the work was performed during the winter or dry season. During the summer season the city is subjected to tropical showers and although the rain seldom lasts for more than a couple of hours, it rains almost every afternoon from May to September with surprising regularity. This is something of a hinderance as the rain is so severe while it lasts that the men cannot work outside.

The climate, however, is not without its advantages as there is no ice or snow to contend with and even the coldest day in winter does not send the temperature much below 65° F.

Labor is somewhat inefficient. The force employed on the work consisted of an engineer-in-chief who exercised a complete control as the company's representative in Havana. Also one assistant engineer who combined the duties of draughtsman, paymaster, inspector, timekeeper and all round utility man. The head foreman was an American with some previous knowledge of the "Gamewell System" and of the Spanish language. There

were two classes of linesmen employed, the first consisting of Americans who were intrusted with connecting up the boxes and circuits and the interior wiring of the station houses. The second class, composed of Spaniards and Cubans, were employed in stringing and tying up the line. In addition to the linesmen a force of laborers was used in erecting the fixtures and poles and also as helpers to the linesmen.

The work was taken precinct by precinct after the following method of procedure. A gang would be started erecting fixtures and poles as located by the head foreman. These would be followed by another gang stringing, pulling up, and tying the wires. After this second gang came the first class linesmen cutting in the branch circuits and connecting up the street boxes. Simultaneously another gang erected the boxes at their proper locations.

Attached to each gang was a mule cart to carry tools, ladders, fixtures, boxes, wire, and other necessary supplies. Each gang had its own foreman or "capatáz" accountable to the head foreman who took a general supervision over all.

Every morning each "capatáz" was obliged to turn in to the inspector a report card showing the work of the previous day; and it was the duty of the inspector to examine and pass upon that work.

All tools and supplies were kept at a central storeroom and workshop where two carpenters were employed in making fixtures and preparing other necessary material.

The wiring of the station houses was left until the last and after the completion of all outside work.

In all, seven precincts out of the twelve were installed, only seven being called for by the contract. These seven precincts constitute the entire city proper, the remaining five in reality being suburbs where the houses are more or less separated from each other by grounds or gardens.

The work was not rushed, it being thought better to employ fewer men and take more time. No work was done on Sundays, and eight hours constituted a working day.

The men started work at 7.00 A. M.

Stopped for breakfast at 10.30 A. M.

Started again at 12.00 M.

And stopped for the day at 4.30 P. M.

The first gang left the storeroom to go to work on January 4, 1901, and the system was completed in every detail by the last week in May following.

The force varied greatly in size from time to time but never exceeded thirty men, and at first and last was much less than that number.

In closing no little praise must be given to the memory of the engineer-in-chief who, unselfishly, with no thought of what successes or triumphs the future might hold in store, gave up his life that the work of the present might be faithfully accomplished.

THE INDUCTION MOTOR.

C. A. ADAMS.

(*Continued from June Issue.*)

IN the first part of this article (in the April number of the Journal), the underlying principles, the structure, and the elementary theory of operation of the induction motor were considered; in the present number a more careful analysis will be made of the currents, e. m. f.'s and fluxes, and their variation with the load.

Currents. When analyzing the effect of the polyphase primary currents in the production of a revolving field, the m. m. f. of the secondary currents was entirely neglected; that is, the analysis applied strictly only to no-load conditions, when the armature speed is nearly synchronous and the secondary current is very small.

But as the load increases, the slip and secondary current increase, at first in nearly the same proportion, and there must be a corresponding increase in the primary current. As in the familiar transformer analysis, this increase in primary current, over and above that necessary to produce the revolving field, may be viewed from two standpoints; either as an energy component to supply the demand for increased power; or as a component whose m. m. f. just balances that of the secondary current; leaving as a total resultant m. m. f. one equal to that of the primary no-load current. This latter is usually called the exciting current. The approximate constancy of the mutual flux and hence of the exciting current will be discussed in the following paragraphs.

Fluxes. As in the case of the transformer, there are three fluxes; that linked with both primary and secondary windings, which may be called the mutual or gap* flux, whose m. m. f. is the resultant of those of primary and secondary currents; that

* Since it crosses the air gap from primary to secondary.

linked with only the primary winding, called the primary leakage flux, and due solely to the m. m. f. of the primary current; and the secondary leakage flux, linked with only the secondary winding, and due solely to the m. m. f. of the secondary current. Each of these fluxes is in phase with its respective m. m. f. except in so far as core losses may give a slight lag to the flux.

As both the primary and secondary windings are distributed along the periphery of the air gap, it is evident that no one of these three fluxes links as a whole with the whole of either winding (see Fig. 11a, page 70), even in the case of a two-pole machine. Thus the primary leakage flux may be defined more exactly as the flux which links with a larger part of the primary than of the secondary. Similarly with the secondary leakage. From this point of view, the leakage fluxes may be considered to a large extent as distortional rather than as independent fluxes. That is, the leakage fluxes when superposed upon the main flux, yield a resultant distorted flux, which is the actual flux. The arbitrary separation of this actual into mutual and leakage fluxes is made as a matter of convenience in calculation and analysis; it is legitimate in calculation only in so far as the reluctance of each path is independent of the flux therein, since it is evidently impossible to calculate with any accuracy the reluctance of a leakage path in iron unless we know the *actual* flux density in that iron. However, in a well designed machine the leakage paths are purposely made of very high reluctance, and therefore as far as possible of non-magnetic material; thus their reluctance may be assumed to be approximately constant, and the calculation of each flux separately, will yield fair results.

This question will be made more clear in a later section which deals with design and calculation.

Electro-Motive Forces. The primary impressed e. m. f. is balanced by three counter e. m. f.'s; that induced by the mutual flux; that induced by the primary leakage flux; and that due to the primary resistance. Of these the first mentioned is predominant, and under normal conditions of operation is rarely less than 95% of the total primary impressed e. m. f., even

at full load. Its variation from no load to full load is thus comparatively small, as must be that of the mutual flux to which it is proportional.

Therefore the exciting current which is (in ampere turns) the resultant of primary and secondary currents, may be assumed roughly constant during the range of normal operation.

Thus far the analysis of currents, fluxes, and e. m. f.'s is exactly similar to that of the transformer, and as long as the secondary of the induction motor is stationary there is no essential difference; but with the rotation of the secondary winding there is introduced into that circuit an additional e. m. f., in opposition to that which would be induced were the secondary stationary, and the algebraic sum of the two is the actual induced or slip e. m. f., E'_2, considered in part I, page 74. When the armature is revolving synchronously, the two opposing e. m. f.'s are equal and E'_2 is zero.

Thus E'_2 may be considered as made up of two opposite components, E_{2_0}, the e. m. f. that would be induced at standstill, and E_{2_r}, the counter e. m. f. of rotation. As these are all produced by the same flux acting on the same winding, their relative magnitudes are as their speeds:

$$\left.\begin{aligned} E_{2_0} &= C \\ E_{2_r} &= C(1-s) \\ E'_2 &= E_{2_0} - E_{2_r} = Cs \end{aligned}\right\} \quad . \quad . \quad . \quad . \qquad (18)$$

where C has the same meaning as in eq. (5), page 74.

Of the resultant induced e. m. f. E'_2, a part is balanced by the counter e. m. f. of resistance, and a part by that of leakage reactance.

The phase relations of these e. m. f.'s, currents, and fluxes will be considered later in connection with the vector diagram.

Current and Flux Distributions. There is another considerable difference between the analysis of transformer operation and that of Induction Motor operation. In the transformer each convolution of the winding links with the whole of the core and of the common flux, whereas in the induction motor the winding is distributed in a plane perpendicular to the flux and there are at any instant some of the turns in each phase which

do not link with all of the flux; also, in a transformer the flux is distributed nearly uniformly over the core section at any instant, whereas it has been shown (Fig. 11, page 70) that three phase sinusoidal currents in a symmetrical, distributed winding, will produce an m. m. f. and flux across the gap, which have at any instant, approximately sinusoidal distributions, and that this wave of flux sweeps around the gap periphery with a uniform velocity. This is equivalent to saying that the flux density at any point along the gap varies sinusoidally with the time.

Thus if we take a loop made up of two similar active conductors (180 electrical degrees apart), the e.m.f. induced therein by the above described flux may be considered as due either to the sinusoidal variation of the total flux linked with that loop, or to the cutting of the sinusoidally distributed flux across the two active conductors.

An inspection of figures 11a to 11e shows that the current distribution is also cyclic, but not as nearly sinusoidal as the flux. With an increase in the number of phases, the current distribution would become more nearly sinusoidal.

For the present assume sinusoidal distributions of current and flux.

Referring to Fig. 19, $\overline{gg}$ is the developed air gap line; above this line is the primary or stator, and below it is the secondary or rotor; flux directed downwards in the figure is thus directed inwards from primary to secondary; this direction will be called positive and will be indicated in the curve by ordinates measured upwards from the gap line.

Current directed outwards from the paper will be called positive and will be so indicated in the curves.

The flux and the armature are assumed to be revolving clockwise (left to right in Fig. 19), the armature less rapidly; therefore the armature revolves counter-clockwise with respect to the flux (right to left in the figure).

Curve I represents by its ordinates the local variation of flux density, b_g, along the gap at any instant. This sinusoidal flux distribution will be assumed as the starting point; we have seen that its magnitude is approximately determined by the impressed e. m. f.

In order to supply the corresponding distribution of magnetic potential difference, there will be required a sinusoidal distribution of magnetizing current, such as shown by Curve II. The

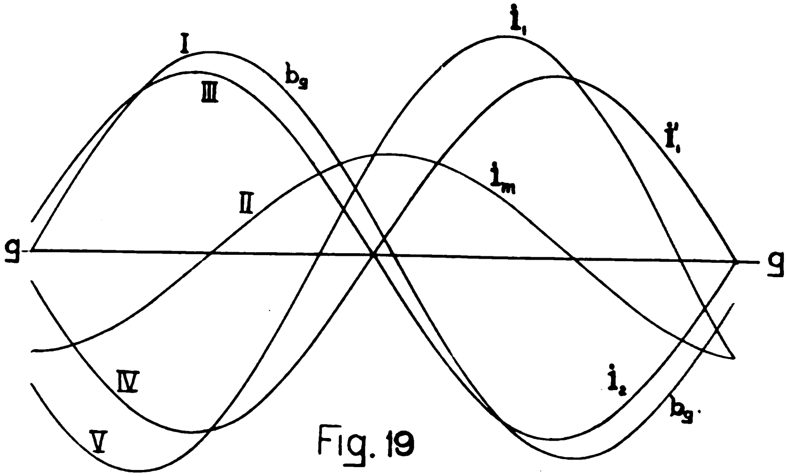


Fig. 19

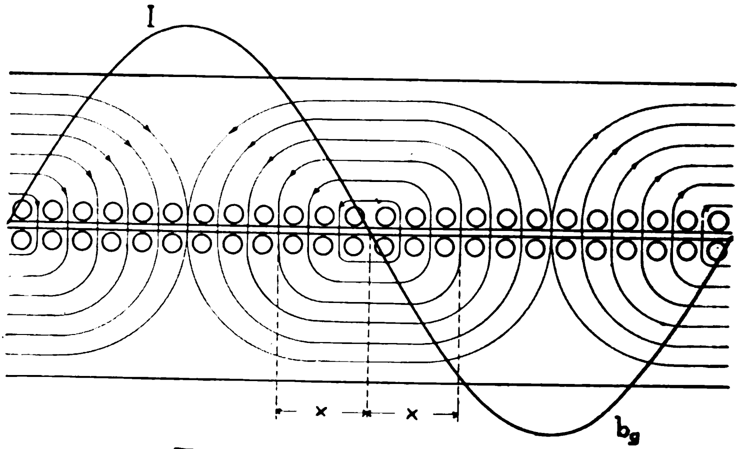


Fig. 20.

reason for this will be made clear by a reference to Fig. 20, where Curve I represents the flux distribution as before, and the light lines show the approximate direction but not the density of the flux.

The gap density at any point $\underline{x}$ may be written, $b_g = B_{g\,max.} \sin \frac{\pi}{\lambda} x$, where λ is the pole pitch and $B_{g\,max.}$ the maximum value of the gap density; but, if the reluctance of the iron be neglected, the number of ampere turns required along the path through $\underline{x}$ will be proportional to the b_g at that point, and is $\underline{Ni}_g = Kb_g = KB_{g\,max.} \sin \frac{\pi}{\lambda} x$. The peripheral current density is then $\frac{d}{dx} (\underline{Ni}_g) = K\frac{\pi}{\lambda}B_{g\,max.} \cos \frac{\pi}{\lambda} x = K\frac{\pi}{\lambda}B_{g\,max.} \sin \left(\frac{\pi}{\lambda} x - \frac{\pi}{2}\right)$ Thus the magnetizing current must have a sinusoidal distribution and be displaced by 90 electrical degrees from the flux.* It has already been noted that a sinusoidal current distribution is only possible with a very large number of phases; but for our present purpose this assumption is very convenient and assists in giving a simple though somewhat inexact picture of the most important induction motor phenomena.

Curve II, Fig. 19, thus represents the distribution of magnetizing current, i_m (constant reluctance and therefore no core losses, assumed), necessary to produce the flux distribution of Curve I.

If the armature is revolving in synchronism with the field, there will be no secondary current, and this exciting current will be the only current in the primary winding.

The factors which determine the phase and magnitude of the secondary current, have already been considered (see Fig. 15, page 77, with context), where Curve II shows the current variation in a single secondary coil as it moves through the field, or, what is equivalent, the current distribution in the several secondary coils, at a given instant, in its proper position with respect to the flux distribution.

* It should be borne in mind that all of the curves under consideration represent *space* distribution at a particular instant, and that the angles are *space* angles (not time phase angles), each representing an arc of gap periphery.

Each point on a curve corresponds to a particular point along the gap periphery and the ordinate represents the flux density or peripheral current density at that point and at the particular instant to which the whole curve or set of curves corresponds.

In Fig. 19, the secondary current distribution is similarly represented by Curve III. If the flux is to remain unchanged, the *resultant* current distribution must also remain unchanged and there must be added to the magnetizing current in the primary a current, i'_1, whose m. m. f. just balances that of the secondary current, i_2. The corresponding distribution curve is thus equal and opposite to the i_2 curve; it is shown in Curve IV.

The total primary current, i_1, is the sum of i_m and i'_1 (Curves II and IV), and is represented by Curve V.

A simple point of view for the curves of Fig. 19 is as follows: imagine the flux to be stationary, the primary structure to revolve backwards (right to left) at synchronous speed and the secondary structure at slip speed; then the ordinates of the current curves at any point show the values of the corresponding currents in their respective coils, when those coils have arrived at that point in the field.

It is thus obvious, from the most fundamental considerations that although the primary and secondary currents have very different frequencies, when considered with respect to their own circuits; their space distributions bear to each other certain definite relations as to space-phase and magnitude, which are constant for any given set of conditions. This is equivalent to saying that the primary and secondary currents have the *same* frequency when referred to the *same* winding; *e. g.* that the secondary current has primary frequency when referred to the primary structure or winding, or when viewed from a particular point thereon.

Vector Diagrams. In Fig. 21 the curves of Fig. 19 are represented by vectors, which may in this case be called space (in distinction from time) vectors, since they designate the relative directions, in electrical degrees, in which the maximum values of the several variables occur, *i. e.*, if the diagram be placed at the centre of a two-pole machine in such a way that the B_g vector points toward the maximum flux density at any instant, the other vectors will at the same instant point to the coils in which the corresponding currents have their maxi-

mum values; or, if the diagram revolves synchronously with the flux, the vectors will continue to point to the maximum values.

Movement from right to left in Fig. 19 corresponds to clockwise rotation in Fig. 21.

Reduction of Secondary Quantities to Primary Turns. Strictly speaking the current curves of Fig. 19 and the vectors of Fig. 21 represent the peripheral current densities: in order to reduce these to the actual currents it is necessary to take account of the numbers of turns in primary and secondary windings, since I_2 and I'_1 are equal only when the numbers of turns in primary and secondary are equal, which is rarely the case. In order to

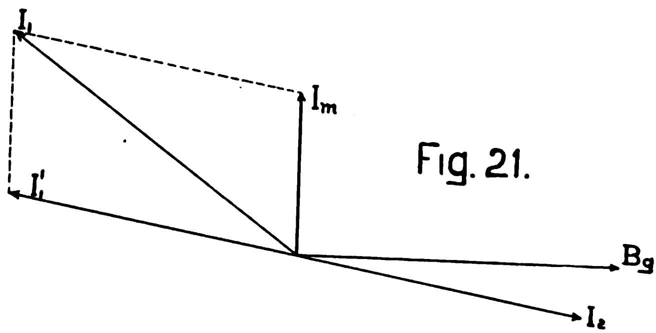


Fig. 21.

avoid the complication of introducing these extra constants, it is customary to reduce all secondary quantities to primary turns, *i. e.*, to imagine the secondary rewound with the same number of turns as the primary, but without changing the amount of copper. *E. g.*, if the secondary has one-half as many turns as the primary, the reduction to primary turns will change the secondary quantities in the following obvious ratios: current, one-half; e. m. f. double; resistance, four times; reactance, four times; percentage resistance drop, the same; percentage reactive drop, the same; power, the same; ampere turns, the same. The two windings are thus exact equivalents, and the substitution entirely legitimate. All vector diagrams will be drawn with this reduction understood.

Time Diagram. In using the diagram to represent time variation, it should be noted (as above for the curves) that the frequency of the secondary current is in general quite different from that of the primary. The primary and secondary variables may then be considered separately; thus, if the primary side of the diagram including $\underline{B}_g$, be revolved counter-clockwise at synchronous frequency, the vertical projections of the several vectors will represent at any instant the instantaneous values of the corresponding variables for a particular primary coil or phase; or if the vectors $\underline{I}_2$ and $\underline{B}_g$ be revolved at slip frequency, their vertical projections will represent the corresponding instantaneous values for a particular secondary coil or phase.

It is possible, however, to interpret the time diagram as a unit by referring the secondary current, not to the secondary structure, but to the primary; *i. e.*, imagine yourself standing at a particular point on the primary and watching the variation of secondary current at that point. This variation is obviously synchronous and independent of the slip, as explained in connection with the curves of Fig. 19.

The diagram of Fig. 21 may now be readily extended to include the several e. m. f.'s and the total flux.

When a coil (*e. g.*, a primary coil) is in the position $\underline{B}_g$, Fig. 21, it is parallel to the mutual flux, and the flux enclosed by it is zero; but when it has revolved through 90° to the position I_m it is perpendicular to the flux and the amount enclosed is a maximum. Therefore the mutual flux vector has the same direction as the magnetizing current, I_m, which is as it should be, see Fig. 22.

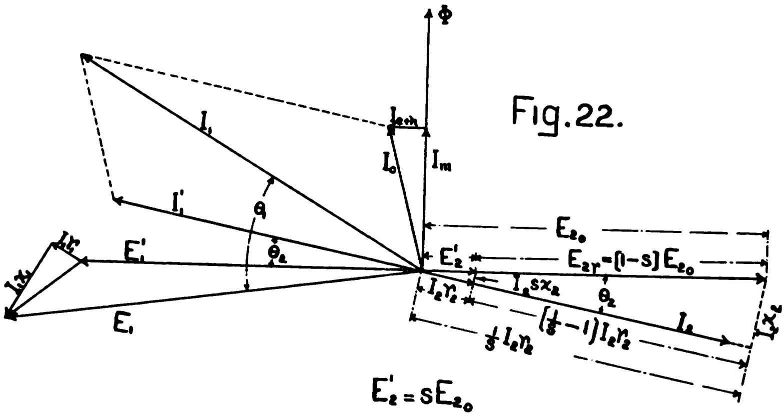
When the plane of a coil is horizontal (Fig. 21), its active conductors are in the strongest field and the induced e. m. f. is a maximum, so that the vector representing the e. m. f. induced in the secondary by the mutual flux will have the same direction as B_g, see Fig. 22, where B_g is omitted to avoid confusion.

The e. m. f. induced in the primary by the mutual flux is in the same phase as E'_2 and B_g and is equal to E_{2_0} (all secondary quantities reduced to primary turns); that part of the impressed e. m. f. required to balance this induced e. m. f. is equal to the

latter but opposite in phase, it is designated as E'_1. To this must be added I_1r_1 and I_1x_1 to balance the counter e. m. f.'s of resistance and leakage reactance.

In the secondary, E'_2 is the actual induced e. m. f. and is consumed by resistance and leakage reactance.

The right angled triangle with hypothenuse E_{2_0} and base along I_2 is of considerable interest, although it is of purely hypothetical origin. As E_{2_0} is the e. m. f. that would be induced in the secondary winding by the mutual flux Φ, were the secondary stationary, $\frac{r_2}{s}$ and x_2 are respectively the resistance and reactance of a circuit such that the e. m. f. E_{2_0} would produce therein the current I_2. In other words the revolving sec-



ondary is equivalent to a stationary secondary identical in all respects except that its apparent resistance has been increased from r_2 to $\frac{1}{s}r_2$. Thus the rotation of the secondary at the speed $1-s$ (in percent of synchronous speed) has the same effect as multiplying the resistance by $\frac{1}{s}$.

In Fig. 22 the core losses are taken account of in the ordinary manner, by adding an energy component I_{e+h} to the magnetizing current, which thus gives the total exciting current I_0.

It will be instructive now to follow the changes that take place in the diagram with change of load. Start with no load and synchronous rotation of the armature, $s = o$, $E'_2 = o$, $I_2 = o$, $I'_1 = o$, $I_1 = I_o$; the decrease in I_1 (from the value shown in the diagram) means less internal impedance drop in the primary, and, if E_1 be assumed constant, which is the ordinary state of affairs, E'_1 will be slightly larger than when the motor is loaded, as will be the flux Φ and the exciting current I_o, since these are approximately proportional to E'_1.

However, Φ, and therefore E'_1 and E_{2_0}, are nearly enough constant within normal range of operation, to make it permissible to take them as the fixed lines of the diagram.

As the load increases, s, E'_2, I_2 and I'_1 increase in about the same proportion, and I_2 begins to lag more and more behind E'_2 (eq. 8, page 75). It is thus evident that if I_o be assumed constant, the locus of the extremity of the I_1 vector starts at the extremity of I_o, when $s = o$, moves at first horizontally to the left, then begins to curve upwards, at first slowly then more and more rapidly.*

Meantime the increased reactive drop in the primary throws E_1 farther and farther ahead of E'_1.

A thorough understanding of the derivation and double interpretation of this diagram forms a splendid foundation for the analysis of many of the very interesting problems which arise in connection with the design and operation of induction motors.

Power Analysis. The power, in watts per phase, delivered to the motor is —

$$P_1 = E_1 \, I_1 \cos \theta_1 \quad . \quad . \quad . \quad . \quad (19)$$

Subdividing E_1 into its three components and omitting the $I_1 \, x_1$ component since it is in quadrature with I, and represents no average power, gives:

$$P_1 = I_1^2 \, r_1 + E'_1 \, I_1 \cos (E'_1 \, I_1).$$

Subdividing I_1 into its two components (I_o and I'_1), gives:

$$P_1 = I_1^2 r_1 + E'_1 I_o \cos (E'_1 I_o) + E'_1 I'_1 \cos \theta_2 \qquad (20)$$

* It will be shown later that this locus is nearly a circle.

But $I_1^2 r_1$ is the primary copper loss and $E'_1 I_0 \cos (E'_1 I_0)$ is the core loss, therefore $E'_1 I'_1 \cos \theta_2$ is the power transmitted across the air gap to the secondary; call this P'_2. Then —

$$P'_2 = E'_1 I'_1 \cos \theta_2 = E_2^{\circ} I_2 \cos \theta_2.$$

Dividing up E_{2_0} into its two portions E'_2 and E_{2_r}, gives:

$$P'_2 = I_2^2 r_2 + E_{2r} I_2 \cos \theta_2 \quad . \quad . \quad . \quad . \quad (21)$$

or P'_2 = Secondary copper loss + Power converted into mechanical form.

The last term may be called the output of the secondary since it is the remainder after all of the losses have been accounted for; it will be designated P_2. Of this output a part is consumed in journal friction and air resistance, and the remainder is available as useful work at the pulley.

The meaning of E_{2_r}, the counter e. m. f. of rotation, thus becomes more clear, since it represents the secondary or motor output, just exactly as does the counter e. m. f. of rotation in any other type of motor.

On the same basis, E_{2_r} may also be compared with the terminal e. m. f. of a static transformer, the only difference being that in the latter case the output is in electrical form, whereas in the motor it is in mechanical form.

It will be observed that all the power represented by E'_2 is consumed by secondary copper loss, and that it corresponds to the internal impedance e. m. f. of the static transformer.

The secondary output is then —

$$P_2 = E_{2_r} I_2 \cos \theta_2 \quad . \quad . \quad . \quad . \quad . \quad . \quad (22)$$

but

$$E_{2r} = (1 - s) E_{2_0} \quad . \quad . \quad . \quad . \quad . \quad . \quad (23)$$

$$I_2 = \frac{s E_{2_0}}{\sqrt{r_2^2 + s^2 x_2^2}} \quad . \quad . \quad . \quad . \quad . \quad . \quad (24)$$

and

$$\cos \theta_2 = \frac{r_2}{\sqrt{r_2^2 + s^2 x_2^2}} \quad . \quad . \quad . \quad . \quad . \quad . \quad (25)$$

Therefore

$$P_2 = E^2_{2_0} \frac{(1-s)\ s r_2}{r_2^2 + s^2 x_2^2} \quad . \quad . \quad . \quad . \quad . \quad . \quad (26)$$

Torque. The mechanical angular velocity of rotation is, $2\pi n (1-s) \div p'$ where p' is the number of pairs of poles. The torque in synchronous watts is then —

$$T = \frac{P_2}{angular\ velocity} = \frac{p'}{2\pi n} E^2_{20} \frac{sr_2}{r_2^2 + s^2x^2_2} \quad . \qquad (27)$$

Since E_{20} is approximately equal to the impressed e. m. f., it thus appears that both output and torque are approximately proportional to the square of the impressed e. m. f. In other respects equations 26 and 27 are of the same form as equation 11, page 79.

Losses and Efficiency. The losses are made up of the core losses, the copper losses, and friction losses.

Core losses. The flux varies throughout the primary core at full frequency n, and as the flux is approximately constant, this part of the core loss is also approximately constant. As a matter of fact, the distortion accompanying the increase of load causes the core loss to increase materially with the load, although not by an easily calculable amount.

The flux in the secondary core varies with slip frequency, which is normally low. Thus the secondary core loss is small except at very low speeds. On account of this low secondary frequency, much higher flux densities are allowable in the secondary core.

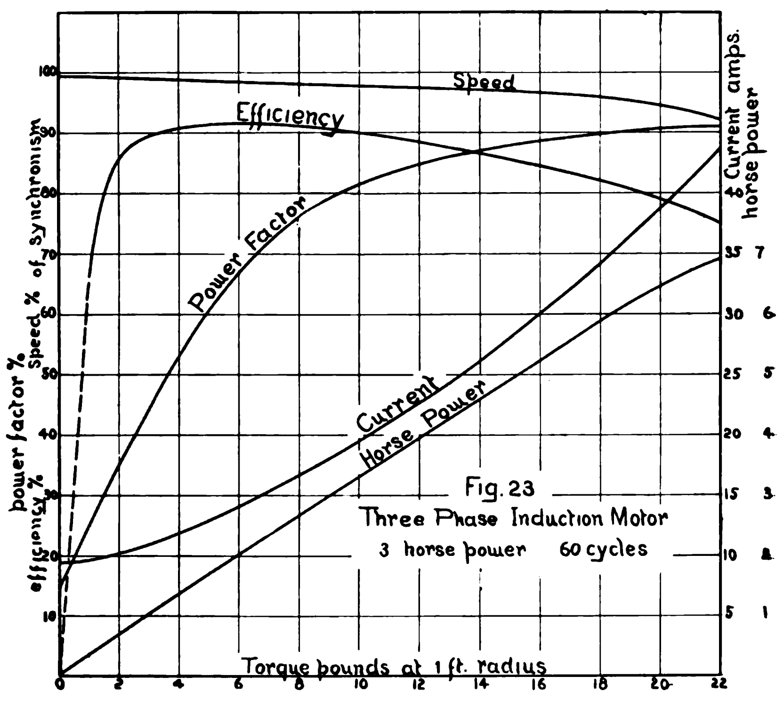
Copper Losses. These are $I^2_1r_1$ and $I_2^2r_2$ and vary approximately as the square of the primary current.

Thus the loss and efficiency curves would look very much as those of a transformer, except that the constant part of the total loss includes not only the core loss but also the friction loss and that part of the primary copper loss due to the exciting current. In the transformer with closed magnetic circuit, the last named item is negligible.

Power Factor. With a given impressed e. m. f. and a given power, the current is inversely proportional to the power factor or cosine of the angle of lag, and it is therefore desirable to make the latter as large as possible, or the angle of lag as small as possible.

An inspection of the diagram, Fig. 22, reveals three causes for the lag of I_1 behind E_1. They are: the magnetizing current I_m; the secondary leakage reactance, which causes I_2 and therefore I'_1 and I_1 to lag; and the primary leakage reactance, which causes E_1 to lead relatively to E'_1, or what is the same thing, increases the lag between I_1 and E_1.

The lag may thus be attributed to two general causes: the magnetizing current, whose magnitude depends largely upon



the length of the air gap; and the magnetic leakage, which will be considered in a later instalment of this article.

The variation of the power factor with the load will appear from the diagram.

Fig. 23 shows observed curves of speed, current, power factor, power, and efficiency, all plotted against the torque, for a 3-H. P. motor. The secondary resistance was unusually low,

too low for satisfactory starting; this accounts for the high efficiency and the good speed regulation.

An analysis of these curves in connection with the vector diagram will repay the student.

In the next instalment of this article there will be developed the mathematical formulae for the variables shown by the curves of Fig. 23.

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Graduate Notes.

G. Johnson, '04, is with the B. F. Sturtevant Co., at the Jamaica Plain works.

A. G. Monks, '04, is engaged in coal mining operations in West Virginia.

A. A. Thayer, '03, is building machine tools in Cincinnati.

J. F. Sanborn, '99, is assistant engineer, employed by the N. Y. Rapid Transit Commission, in charge of Division of the East River Tunnel.

The following members of the class graduating last year, are employed by the New York Rapid Transit Commission:

H. M. Hale, '04, C. Gilman, '04, and D. G. Edwards, '03, in the division of subway work.

W. L. Hanavan, '03, E. W. Smith, '04, and J. P. Hogan, '04, in the division of elevated railroad work.

T. Lindsley, '04, K. P. Emerson, '04, and D. W. Howes, '03, are in the division of the East River Tunnel.

F. H. Poor, '04, and Delafield DuBois, '04, are in the testing department of the General Electric Co., at Schenectady.

H. W. Locke, '02, is with Westinghouse, Church, Kerr & Co., on the Pennsylvania Railroad tunnel at New York. C. D. Burchenal, '02, is with the same company in the New York office.

D. C. Barnes, '04, is with Ford, Bacon & Davis of New York. He is temporarily located at their station at Little Rock, Ark.

J. C. Davenport, '04, is with the Bullock Electric Co., at Cincinnati.

M. King, Jr., '04, is in the testing department of the Western Electric Co., in New York.

C. H. Fisher, '04, is with the Telluride Power Co., at Provo, Utah.

D. C. Wright, '04, is in the draughting department of the Electric Controller & Supply Co., at Cleveland.

G. C. Crawford, '04, is teaching electrical engineering at the University of North Carolina at Chapel Hill, N. C.

Architectural Notes.

The architect Mr. McKim, wishing to place at an important point in the new University Club in New York, the figure of some one who best represented the spirit of the University man of all the ages, asked President Eliot who, to his mind, best

typified this ideal. It is significant that the President should have unhesitatingly named the artist Leonardo da Vinci. It is equally significant that when Prof. Shaler wished to set before the Engineering Society a broad and high ideal he should have chosen the same great painter. He said that it was not only because he so early displayed the modern scientific spirit by both his method of first collecting the facts, second, illuminating them with the imagination and last by criticising the result, but also because of his eager spirit and because all of his productions were explorations along new lines.

He was painter, architect, sculptor, inventor, and, as one may imagine, a splendid example of the physical man as well.

His wonderful attention to detail was as remarkable as his breadth of ideas, and so both of these qualities he is inspiring, at the present day. Many older critical authorities have found him wanting in actual achievement compared to other painters and scientists, but it is realized more than ever to-day that it was his spirit which was vital and inspiring, and which made his pictures, his inventions, and his life wonderful to all who believe in the power of ideas.

It is fitting that his name should appear here in an Engineering Journal, for the best Architects and Engineers strive to keep alive in themselves, in the stress of their professional work, that passionate desire for knowledge and at least an appreciation of such an ardent love of beauty as was Leonardo's.

L. P. Burnham, '02A, the holder of the Nelson Robinson, Jr., Fellowship in Architecture for 1903–04, has been appointed to the Julia Amory Appleton Fellowship, recently established by Mr. McKim at Harvard, in memory of his wife, and will study at the American School in Rome during the winter.

C. R. Wait, '03A, the present holder of the former fellowship, is now in England. E. B. Lee, the first holder, has returned from Paris and has gone into partnership in Pittsburg, Pa.

Eliot T. Putnam, '01, is at present working in Paris in addition to those men named in the April number of this magazine.

W. B. Bragdon, '01A, is in the office of Messrs. McKim, Mead & White, in New York, as is also G. S. Parker, '00A.

S. E. Somes, '01A, is in the office of Messrs. Bacon & Hill in Boston.

C. H. Ely, s. '98, is in independent practice in Beverly, Mass., and has recently designed and executed an interesting bank building in that city.

W. E. Nagro, '98A, is practising in Newport, R. I.

Trade Notes.

One evidence that manufacturers and jobbers in the electrical trade anticipate a very active business for the next few months and for some time to come, is shown by the fact that the Central Electric Company of Chicago, one of the oldest and largest electrical houses in the business, have just increased their warehouse capacity about 50% and have added very largely to their floor space.

This addition has been made necessary to enable the Central Electric Company to handle their constantly increasing business and to give their patrons more efficient service. The company will carry a very much larger stock, will enlarge their shipping room to a great degree, and will, in short, make a number of changes which are bound to help them in handling their trade.

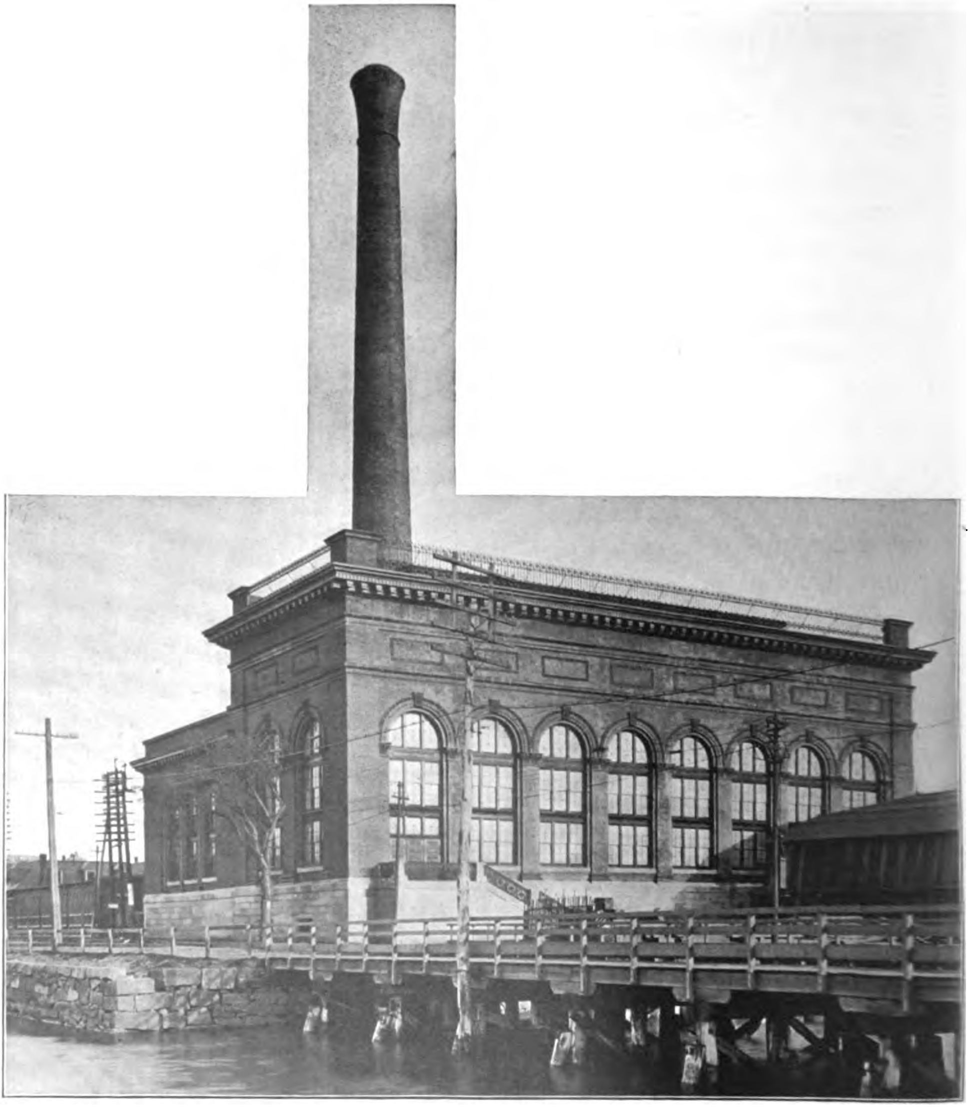
Two circulars from F. W. Weber and Company, Philadelphia, describe Riefler's New Dotting Instrument and Right Line Fountain Pen. With the Dotting Pen, dotted lines either straight or circular can be drawn by an easy interchange of ratchet wheels. The Fountain Pen should be much appreciated by professional draughtsmen on account of its simplicity and neatness.

A. Leschen and Sons Rope Company of St. Louis have a new rope gauge or caliper. This will be useful to all who handle wire rope, for by its use the diameter of any size rope may be quickly determined. This gauge can be carried very conveniently in the vest pocket. It will be sent gladly on request.

Ten new Bulletins published by the Electric Controller and

Supply Company of Cleveland, Ohio present in a condensed and easily read form the general scope and application of their machinery.

The pamphlets contain fine illustrated descriptions of their controllers, brakes, switches, fittings, resistance units and lifting magnets. The illustration shows one of their Pig Magnets in operation.



Cambridge Electric Light Station.

HARVARD ENGINEERING JOURNAL

Devoted to the interests of Engineering and Architecture at Harvard University

VOL. III JANUARY, 1905 NO. 4

TEST OF THE POWER PLANT OF THE CAMBRIDGE ELECTRIC LIGHT COMPANY.

BY LIONEL S. MARKS, ASSISTANT PROFESSOR OF MECHANICAL ENGINEERING.

THE new power plant of the Cambridge Electric Light Company, situated on the Charles River next to the Western Avenue bridge, supplies alternating current at 2300 volts for lighting and power purposes in the city of Cambridge. Its present rated capacity is 2700 K.W. and provision is made for an increase to 4200 K.W. The plant was put in operation early in the year 1903, and was subjected to a series of tests in April and May of the same year for the purpose of determining whether the different parts of the plant fulfilled the builders' guarantees, and also for ascertaining the performance of the plant under various conditions of running. The observations on these tests were made by students of engineering in Harvard University, of the classes of 1903 and 1904. The object of this paper is to present some of the results of these tests.

The general arrangement of the plant is shown in the sectional elevation, fig. 1, and the partial plan, fig. 2. The boiler floor level is considerably below the engine floor level; the basement is still lower. This arrangement leaves nearly 14 ft. clear height in the basement, and gives excellent space for the primary heaters, air pumps, exciter engine, and the rest of the machinery there installed.

There are two batteries of Babcock & Wilcox boilers, two

boilers in each battery. Each boiler has 3964 sq. ft. of heating surface, 67.6 sq. ft. of grate surface, and 125 sq. ft. of superheater coils. The chimney is independent of the building and rises 252.5 ft. above the grates. The feed pumps (see fig. 6) are Blake duplex outside-packed plunger pumps driven by tandem compound steam cylinders. The feed passes through a main heater in the main engine exhaust pipe, through the closed

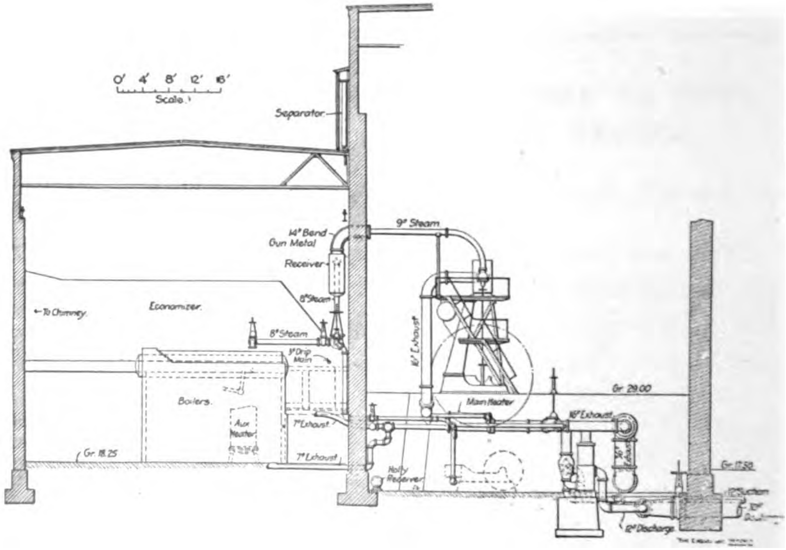


FIG. 1. — CROSS-SECTION OF THE STATION.

auxiliary heater (D, fig. 6), where it receives heat from the feed pump and air pump exhausts, and then through a Green economizer to the boiler. The economizer is carried high above the boiler room floor, immediately over the feed pumps and auxiliary heater. All the high pressure drips connect with a Holly return system.

The condensers are Blake vertical twin jet condensers, — the condensing water is taken directly from the Charles River.

The Engines.

The engines were built by McIntosh, Seymour & Co., of Auburn, N. Y. They are vertical, high-speed, two-cylinder, cross-compound, direct-connected units with overhanging cranks. Each cylinder is supported on a heavy, hollow, cast-iron frame

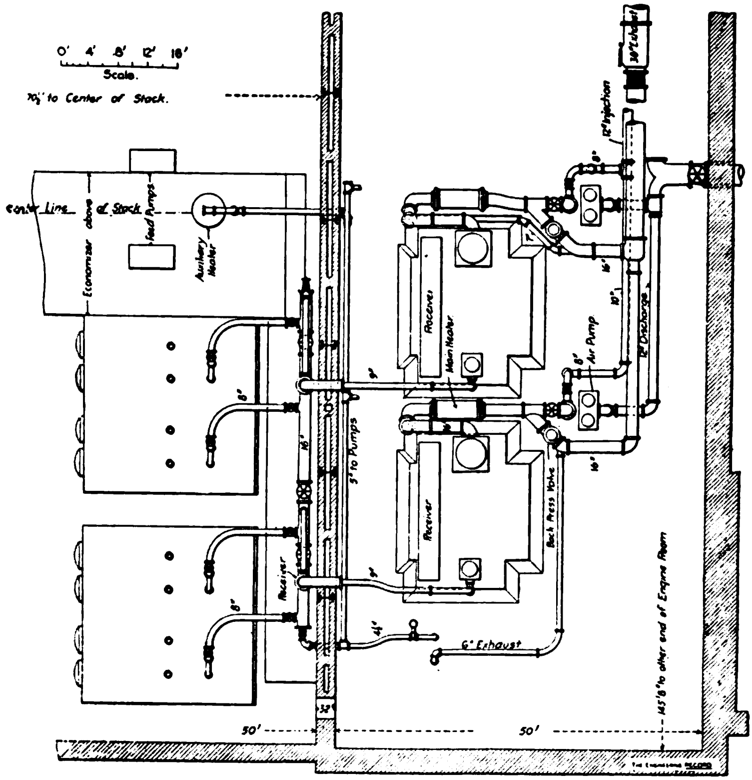


FIG. 2.—PARTIAL PLAN OF THE STATION.

at the back and on two inclined steel standards in front. Each H. P. cylinder is jacketed on the barrel and both heads and the jackets are piped in series; the steam enters the jacket on the top head, passes into the barrel jacket, goes to the jacket on the lower head and then to the reheater coils. In this way a

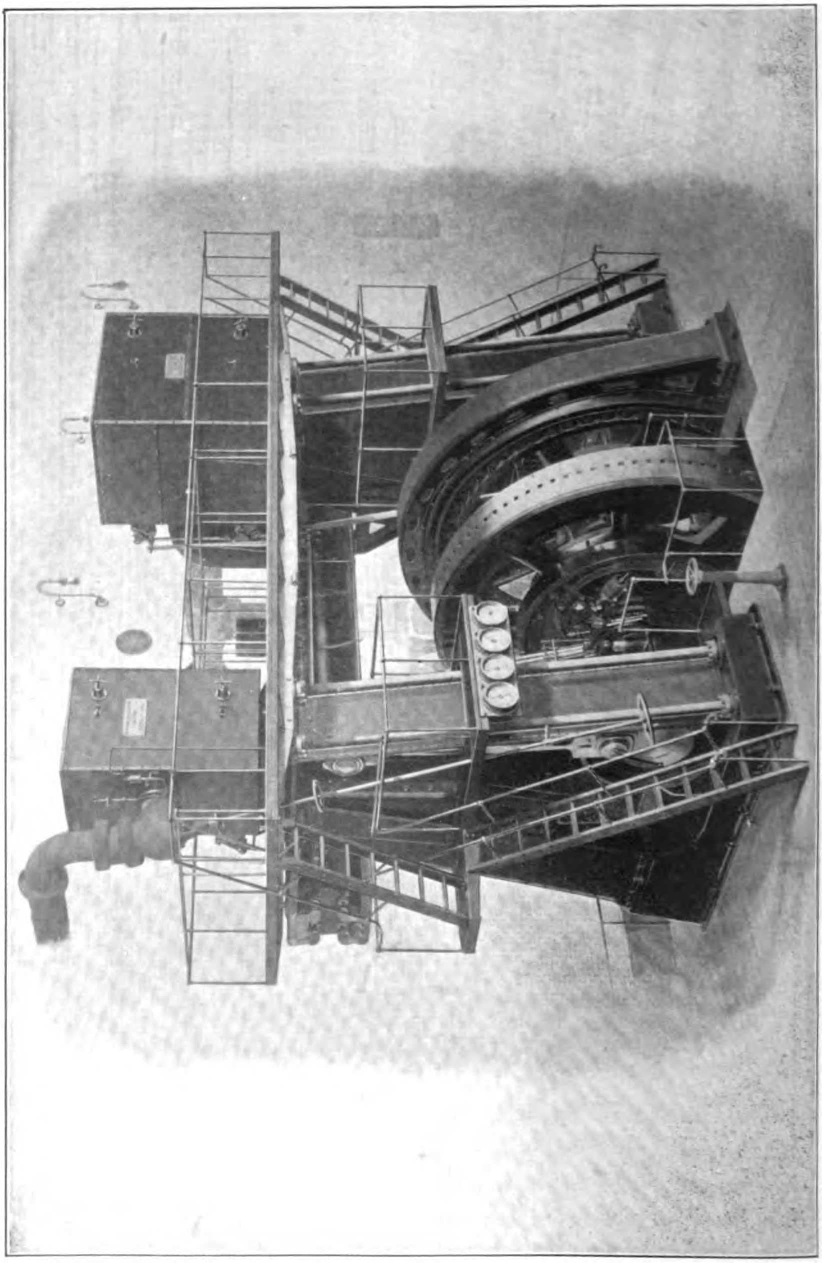


FIG. 8.— EXTERNAL VIEW OF ENGINE.

very active circulation in the jackets is ensured. As there is no separate steam supply to the reheater coils, nor any separate drain from the H. P. jackets, it is not possible to use either jackets or reheater alone. The receiver is a large cylindrical drum at the back of the engine and close to the cylinders. The

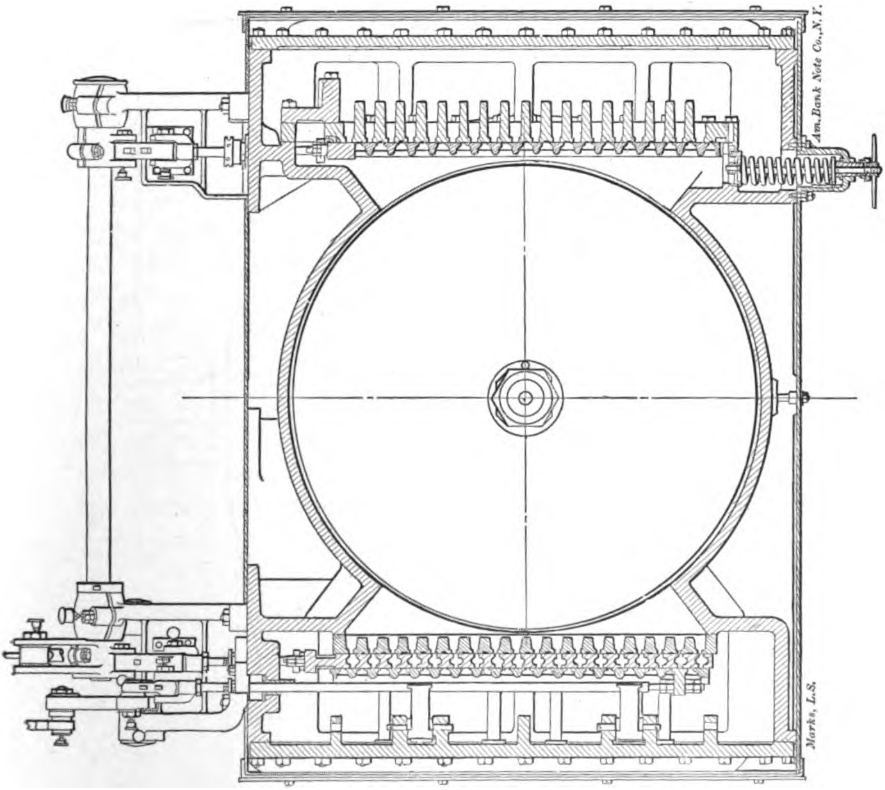


FIG. 4.—SECTIONAL PLAN OF L. P. CYLINDER.

reheater consists of one or more coils of pipe in the receiver. The L. P. cylinder is unjacketed.

The valves are of the flat, gridiron type, unbalanced and of short stroke. The steam valves on both H. P. and L. P. cylinders consist of a main valve cutting off at about .8 stroke, and a Rider cut-off valve, the movement of which can be varied so as to give any desired cut-off. The main steam valves and the

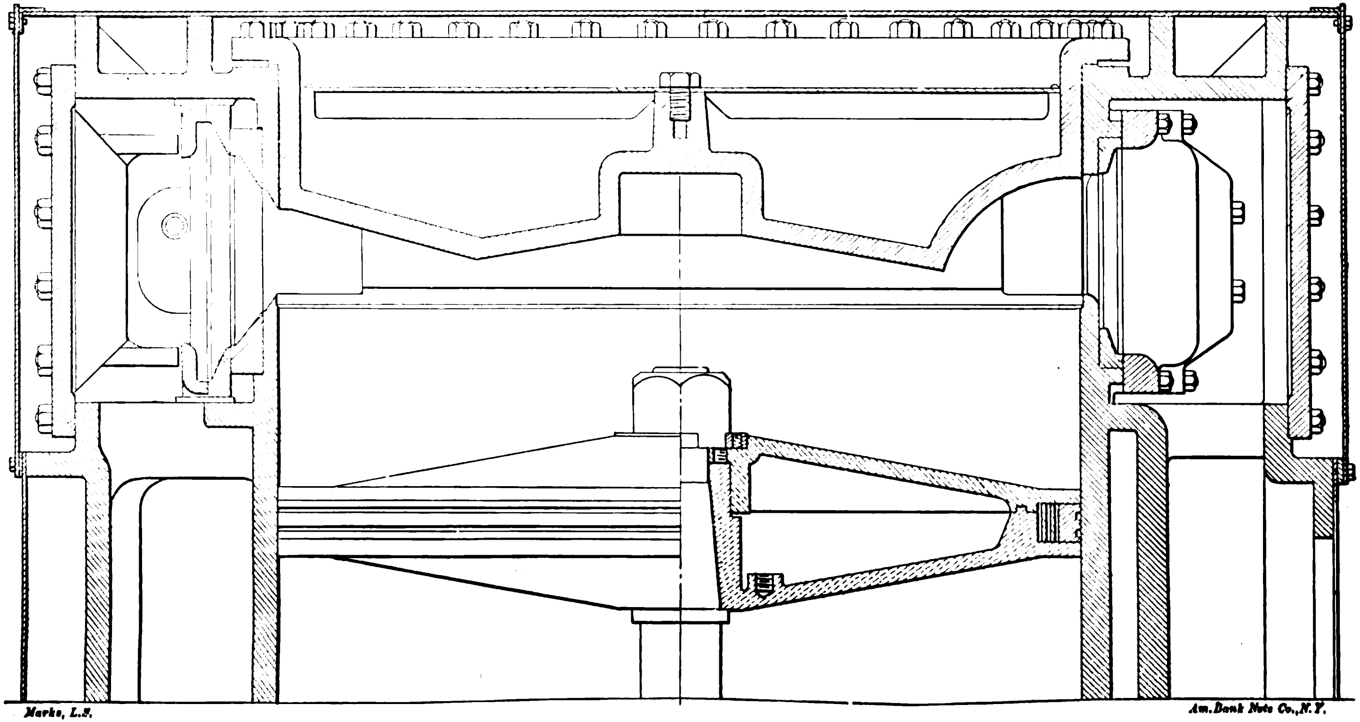


FIG. 5.— PARTIAL SECTIONAL ELEVATION OF L. P. CYLINDER.

exhaust valves on each cylinder are driven from an eccentric on the main shaft through a system of links and levers. The cut-off valves are driven by auxiliary eccentrics which are controlled by a fly-wheel governor. The action of the valves is rapid; the openings for admission and exhaust of steam are large.

The fly-wheel governors are designed to control the speed within two per cent. variation between zero load and full load. The position of the governor weights can be regulated when the engine is running by means of a small electric motor fastened to the fly wheel and controlled from the switch-board. This device is valuable for synchronizing in parallel running.

Engines 1 and 2 are exactly similar units, 18 inches and 38 inches by 42 inches, developing 760 indicated horse-power at .24 cut-off with 135 pounds initial steam pressure and 26 inches effective vacuum, and direct connected to 600 kilowatt, 60-cycle alternating generators built by the General Electric Company. Engine 3 has cylinder dimensions 31 inches and 64 inches by 48 inches, develops 2,320 indicated horse-power at .24 cut-off with 135 pounds initial steam pressure and 26 inches effective vacuum and is direct connected to a 1,500 kilowatt General Electric generator.

The Arrangements for Testing.

As the engines are fitted with jet condensers, their steam consumptions had to be determined by measuring the boiler feed. This necessitated the adoption of adequate precautions to prevent leakage from the feed mains, from the boilers and from the steam pipes. The feed was from a pump which handled only the water going to the main boilers. These boilers supplied steam only to the engine under test; they were examined for general tightness and were shut off from the Holly return system and had their blow-offs disconnected. The steam on its way to the engine under test went first to a section of the main steam header, which was isolated by gate valves from the rest of the header. These gate valves were tested for tightness with full steam pressure on one side and atmospheric pressure on the other, and were found practically tight in all cases. In

order, however, to prevent even slight leakage the steam pressures were kept the same on both sides of the valves during the tests. In all the tests, the steam supply to the engines was superheated so that the steam pipe drips could be closed.

The total leakage from the boilers and steam pipes was determined by leakage tests after nearly every run. To make the leakage test, the fires were allowed to burn down at the end of the run and were kept in such condition as just to be able to maintain the steam at the test pressure when the supply to the engine was shut off completely. The observation of the rate of lowering of the water level in the boilers under these conditions gave the necessary information for determining the rate of leakage loss from the boilers and steam pipe.

The feed heaters and economizer were tested and found to be tight. The reheater coils were also found to be tight except in one engine, and in that case the only run made was without the reheater in use.

The weight of steam condensed in the jackets and reheater, when these were in use, was determined by collecting the condensed steam in a vessel of known capacity provided with a gauge glass. The drainage from the receiver was determined in a similar way. The arrangement of jackets and reheater prevented the separate determination of the amounts of condensation occurring in each.

During the tests the whole of the steam generated in the plant was used for the engine under test and for its auxiliaries. The main engine was supplied from one or more main boilers; the auxiliary engines from an auxiliary boiler. The feed to the main boilers was weighed. The feed to the auxiliary boiler went through a separate pump, and its amount was determined by subtracting the weighed amount going to the main boilers from the meter reading of the total feed to all boilers. As the meter calibration was found to be rather variable, the amount of water so determined going to the auxiliary boiler is possibly in error by a small amount. The steam pressure in the main and auxiliary boilers was kept the same, so as to prevent leakage past those valves in the steam header which shut off the main from the auxiliary steam.

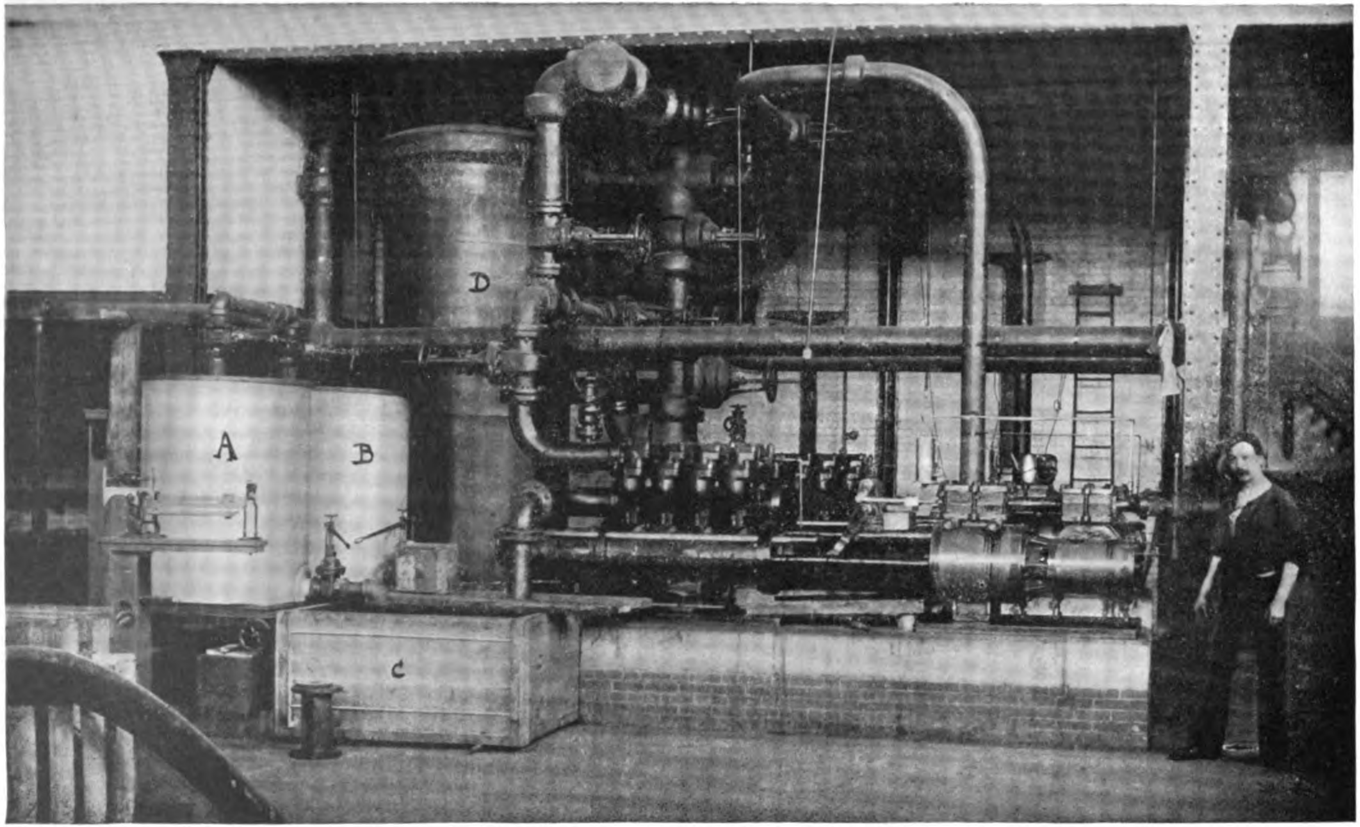


FIG. 6.—THE FEED PUMP, WEIGHING TANKS, AND AUXILIARY HEATER.

The arrangement for weighing the feed to the main boiler is shown in fig. 6. The water was weighed in the galvanized iron barrels A and B, and was discharged into the wooden feed tank C.

The diameters of all the cylinders were gauged when hot. The clearances were not measured directly; the values used for the calculations were given by the engine builders and were determined by them from the working drawings.

The weighing scales were examined by the local sealer of weights, and their accuracy was ensured by further proving with special test weights. All gauges, thermometers and indicators were calibrated. The water meter was calibrated during each run and the weight of water going to the main boiler was checked by feed pump displacement observations.

The load on the engine was entirely electrical and consisted of the station load supplemented by an adjustable water rheostat load. There was no difficulty in any of the tests in keeping the total load constant.

The current for feed excitation was obtained from the main generator.

All observations were taken by thirty-four students of engineering at Harvard University. The electrical measurements were obtained under the supervision of Mr. S. E. Whiting.

Observations were taken at ten minute intervals, and the tests lasted from eight to ten hours.

The Tests.

The principal object of the tests was to determine the steam consumption per I. H. P. per hour of each of the engines at its rated load, but the tests were extended so as to determine the performance of the engines at other loads, and also to find the value of the jackets and reheaters. Incidentally, also, some observations were obtained on the performance of the boilers, economizer, and other parts of the plant.

Engine No. 1 was apparently in first class running condition. The following tests were made on it: —

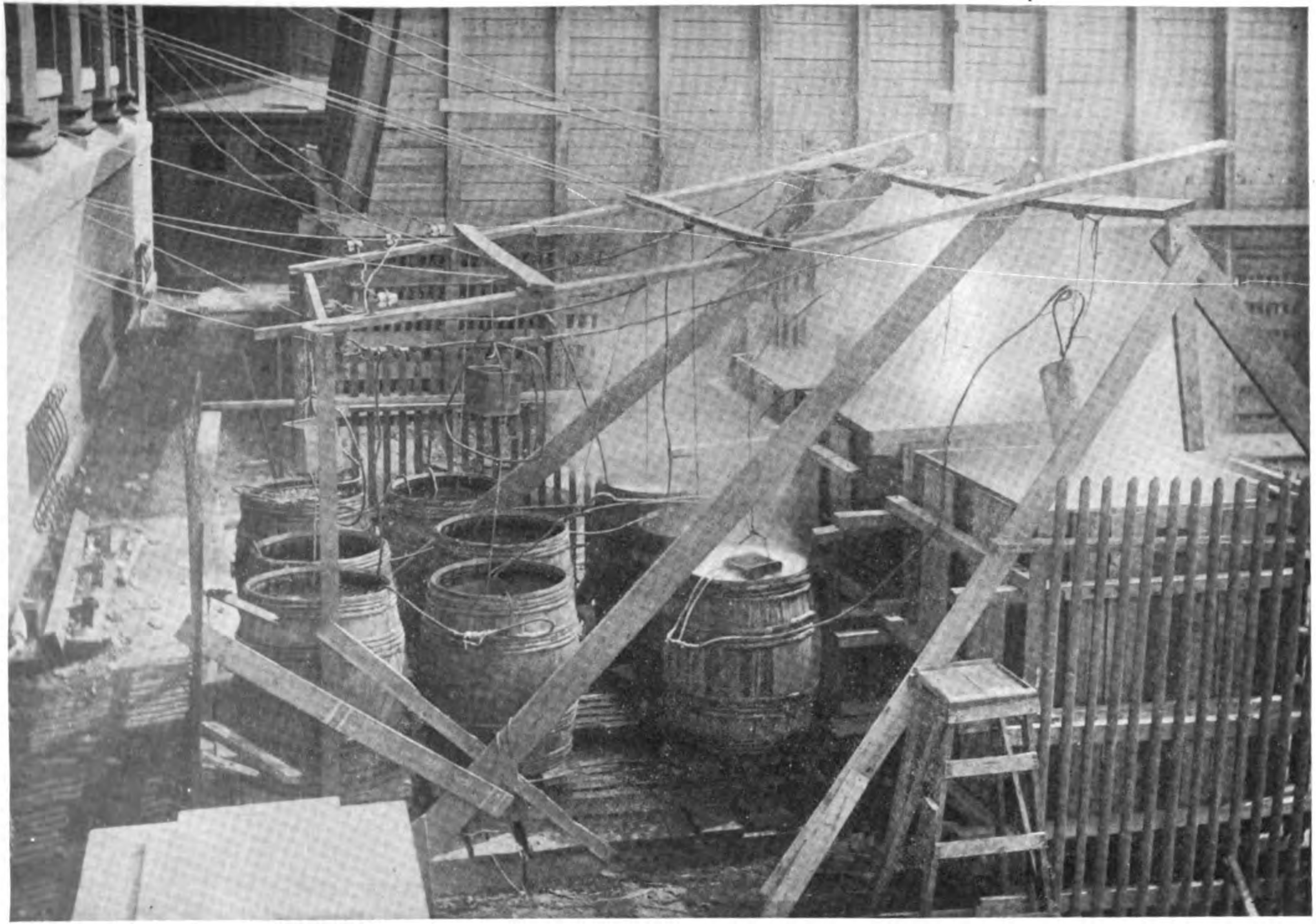


FIG. 7.-- THE WATER RHEOSTATS ABSORBING 1500 K. W.

April 29. A preliminary run was made to accustom observers to their stations and to determine the desired working conditions.

April 30. The first complete test was made on this day. The engine was run without steam supplied to the jackets or reheater. The test was at the rated load and lasted ten hours, during which time the desired conditions were maintained very constant.

May 1. On this day the engine was run with the same load as on the previous day. The only difference in the conditions was that steam was admitted to the jackets and reheater. The conditions were very constant during the test, which lasted for ten hours.

Engine No. 2 was not tested with steam in the jackets and reheater, because of the existence of a slight leak in the reheater coil. The only test was with an overload of about 20%. The run lasted about nine hours on May 7, the conditions being very constant.

Engine No. 3 had been run very infrequently before the tests, and consequently was not in such good condition for testing as the two other engines, which between them had been carrying the station load for some months. The preliminary run on May 4 showed the valve setting to be imperfect, and also showed that the governor was sticking. The tests had to be postponed until these defects could be remedied.

May 15. On this day the engine was run at its full rated load, with steam in the jackets and reheater. The test lasted ten hours, the conditions being very constant.

May 18. The engine was run at half load, with steam supplied to jackets and reheater. The test lasted eight hours.

May 20. The engine was run at quarter load on this day, with steam in the jackets and reheater. The test lasted eight hours.

May 21. On this day was made the only test on engine No. 3 without steam supplied to jackets and reheater. The load was one-half load, the same as on May 18.

With the light loads on this engine, the governing was

not very perfect. There was occasionally some tendency to hunt when the load on the engine varied. It was found impracticable to take friction cards from this engine for that reason.

The principal results of the engine tests are exhibited in the following table. The combined indicator cards for the seven tests are given in figs. 8 to 14.

Line 64 of the table gives the actual steam consumption of the main engine per I. H. P. per hour, and shows the performance of the large unit to be better from full to quarter load than the best performance of the smaller units. When the steam used by the auxiliaries is taken into account, the total steam per I. H. P. per hour continues less in the big unit from full to half load. The practically important efficiency, however, is the total steam consumption per K. W. per hour. The noteworthy result is brought out that the large unit is as efficient at half load as the small units at full load or at overload.

The Value of H. P. Jackets and of Reheating.

The tests of April 30 and May 1 on engine No. 1 are under identical conditions except that the jackets and reheater were not in use on the earlier day. Similarly, the tests of May 18 and May 21 on engine No. 3 were under identical conditions except that no steam was in the jackets and reheater on the second day. An examination of the results given in line 75 shows in both cases a saving of over 7 % resulting from the use of the jackets and reheater.

There are certain facts which the writer believes may be postulated with reference to the effectiveness of jacketing and reheating, and which are supported by the results of these tests. The saving by jacketing varies with the following factors:

(*a*) It increases as the cut-off becomes earlier.

(*b*) It decreases as the superheat of the entering steam increases.

(*c*) It decreases with increase in size of the engine.

There is no saving by reheating when the reheater does no

Results of Tests on the McIntosh and Seymour Engines at the Cambridge Electric Light Station.

	Test Number	1	2	3	4	5	6	7
1	Date of Trial	*April 30.*	*May 1.*	*May 7.*	*May 15.*	*May 18.*	*May 20.*	*May 21.*
2	Number of Engine	**No. 1.**	**No. 1.**	**No. 2.**	**No. 3.**	**No. 3**	**No. 3.**	**No. 3.**
3	Condition of Test	*Full load without reheater.*	*Full load with reheater.*	*Overload without reheater.*	*Full load with reheater.*	*Half load with reheater.*	*Quarter load with reheater.*	*Half load without reheater.*

CYLINDER DIMENSIONS.

4	Diameter H. P. Cylinder	18.00″	18.00″	18.024″	31.037″	31.037″	31.037″	31.037″
5	Diameter L. P. Cylinder	38.03″	38.03″	38.05″	64.035″	64.035″	64.035″	64.035″
6	Diameter of Piston Rod	5″	5″	5″	5½″	5½″	5½″	5½″
7	Clearance H. P. Cylinder, per cent.	4.9	4.9	4.9	6.1	6.1	6.1	6.1
8	Clearance L. P. Cylinder, per cent.	3.95	3.95	3.95	8.1	8.1	8.1	8.1
9	Ratio L. P. to H. P. Displacement	4.595	4.595	4.595	4.318	4.318	4.318	4.318
10	Number of Boiler	No. 2	No. 2	No. 4	Nos. 3 & 4	No. 4	No. 4	No. 4

STEAM WEIGHTS.

11	Water per hour to main boilers, lbs.	10,314	9,680.7	11,523	27,701	14,850	9,518	15,697
12	Leakage per hour from main boilers, lbs.	212	212.	265	505	239	239	239
13	Steam per hour to main engine, lbs.	10,102	9,468.7	11,258	27,296	14,614	9,279	15,458
14	Water per hour to auxiliary boiler, lbs.	2,279	1,387.7	3,077	4,110	3,252	2,625	2,896
15	Leakage per hour from auxiliary boiler, lbs.	80	80	80	80	80	80	80
16	Receiver drain per hour, lbs.	338.7	65.9	691.2	242	91	0	425
17	Reheater drain per hour, lbs.	—	616	—	1,333	1,065	840	—
18	Perc't'ge of steam going to H. P. cyl., drained from receiver,	3.35	.69	6.12	.93	.67	0	2.75
19	Percentage of total steam used in reheater	—	6.45	—	4.89	7.28	9.05	—

PRESSURES AND TEMPERATURES.

20	Steam pressure at throttle gauge	137.8	139.5	133	138.5	134	137.8	136.5
21	Receiver pressure, absolute	23.6	25.8	27.8	25.3	19.8	16.2	18.3
22	Vacuum in condenser, inches of mercury	26.15	26.27	26	25.4	26.4	26.4	25.8
23	Temperature of steam at main boiler, Fahr.	447°	450.8°	430.[illegible]	441.5°	446°	439.5°	450.1°
24	Temperature of steam at throttle, Fahr.	431°	434.8°	411.9°	423.1°	426.7°	413.8°	431.3°
25	Fall of temperature between boiler and throttle, Fahr.	16°	16°	18.8°	18.4°	19.3°	25.7°	18.8°
26	Superheat of steam entering engine Fahr.	72.2°	75°	55.5°	64.2°	70.2°	55.3°	73.5°
27	Temperature of steam entering receiver, Fahr.	237°	241.7°	244.7[illegible]	243.3°	226.6°	216.8°	223.7°
28	Temperature of steam leaving receiver, Fahr.	237°	290.9°	244.[illegible]°	283.6°	285.6°	296.9°	223.7°
29	Superheat entering L. P. cylinder, Fahr.	0°	49.1°	0°	40.3°	59°	79.1°	0°
30	Temperature of L. P. exhaust, Fahr.	125.7°	125.2°	133.9°	133.7°	125.4°	121.5°	129°
31	Temperature of cold feed, Fahr.	53.6	54.1°	54°	56.2°	60°	63.9°	62.1°
32	Temperature of feed leaving heater, Fahr.	124°	125°	130.6°	131.5°	125°	120.8°	128.5°
33	Temperature of feed leaving auxiliary heater, Fahr.	212.9°	201°	210°	201.1°	219.7°	218.4°	218.7°
34	Temperature of feed leaving economizer, Fahr.	215.4°	223°	245°	252.1°	234°	237.9°	255.0°
35	Temperature of injection water, Fahr.	55.3°	56.2°	55°	62.1°	69.6°	66.6°	68°
36	Temperature of condenser discharge water, Fahr.	87.8°	90.2°	85.8°	95.5°	92.1°	84.5°	94.6°
37	Calculated ideal feed temperature, Fahr.	133°	144°	137°	162.5°	143.3°	143°	131.6°
38	Heat per lb. of steam above ideal feed temperature, B. T. U	1,124.8	1,115.7	1,111.3	1,091.8	1,112.8	1,106.6	1,126.5
39	Boiler horse-power	324	303	349	839	459	291	476

INDICATOR CARD MEASUREMENTS.

40	Init. steam press. from H. P. cards, lbs per sq. in., head end,	126.4	133.4	130	132.9	120.35	84	120.5
41	Init. steam press. from H. P. cards, lbs. per sq. in., crank end,	130.9	136.9	129	131.4	122.4	95	126.1
42	Effective vacuum from L. P. cards, lbs. per. sq. in., head end,	11.82	11.91	11.8	11.96	12.42	12.54	12.22
43	Effective vacuum from L. P. cards, lbs. per sq. in., crank end,	11.70	12.17	11.64	11.75	12.43	12.48	12.22
44	Commercial Cut-off per cent. stroke H. P., crank	.285	.260	.363	.217	.063	.069	.074
45	Commercial Cut-off per cent. stroke H. P., head	.266	.225	.331	.187	.071	.050	.0945
46	Commercial Cut-off per cent. stroke L. P., head	.338	.288	.331	.269	.145	.10	.148
47	Commercial Cut-off per cent. stroke L. P., crank	.354	.303	.329	.248	.162	.112	.157
48	Commercial ratio of expansion	16.81	19.28	13.64	21.4	54.3	68.86	49.9
49	M. E. P., H. P. cylinder, lbs. per sq. in.	62.75	56.19	74.60	54.95	29.19	15.93	29.3
50	M. E. P., L. P. cylinder, lbs. per sq. in.	12.26	13.55	14.52	12.30	6.37	4.14	5.98
51	Equivalent M. E. P. referred to L. P. cylinder	25.29	25.16	30.11	24.03	12.92	7.79	13.03
52	Revolutions per minute	118.4	119.1	119.15	116.90	119.11	119.34	118.37
53	Piston speed, ft. per minute	828.8	833.7	834.05	935.20	952.88	954.72	946.96

POWER.

54	I. H. P., H. P. cylinder	383.9	347.1	463.3	1,063.8	604.7	330.8	646.8
55	I. H. P., L. P. cylinder	330.8	368.4	394.3	1,120.2	591.2	385.2	551.3
56	Percentage of total power developed in H. P. cylinder	53.7	48.6	54.0	48.8	51.0	46.2	54.5
57	Total I. H. P.	714.7	715.5	857.6	2,184	1,195.9	716	1,198.1
58	Diagram Factor	.74	.85	.77	.87	.90	.83	.82
59	Electrical Load K. W.	491	485	577	1,543	787	418	782
60	Electrical H. P.	659	651	774	2,069	1,055	561	1,048
61	I. H. P. less electrical H. P.	55.7	64.5	83.6	115	140.9	155	150.1
62	Friction H. P.	50	50.3	50				
63	Mechanical efficiency at rated load	93.4	93.4	93.4				

WATER RATE AND EFFICIENCIES.

64	Steam per I. H. P. per hour in engine, lbs.	14.13	13.21	13.13	12.50	12.22	12.95	12.90
65	Steam in jackets and reheater per I. H. P. per hour, lbs.	—	.85	—	.61	.89	1.17	—
66	Apparent quality of steam at cut-off, H. P. cylinder, per cent.	76	85	86	92	83	81	80
67	Apparent quality of steam at release H. P. cylinder, per cent.	75	88.5	83	93	82.5	88	92
68	Apparent quality of steam at cut-off, L. P. cylinder per cent.	84	89	84	93	92	97.4	80.5
69	Apparent quality of steam at release, L. P. cylinder, per cent.	87	93.2	82	97	96	100	94
70	Steam per K. W. per hour (gross output) in engine	20.5	19.52	19.51	17.72	18.59	22.2	19.76
71	B. T. U. in main engine per I. H. P. per minute	264.9	245.5	243.3	227.3	226.6	241.47	244.02
72	Thermodynamic efficiency	16.01	17.34	17.43	18.7	18.72	17.61	17.4
73	B. T. U. per I. H. P. per minute for Rankine cycle	166.3	165	167.5	168.6	166	161.3	164.7
74	Ratio of engine efficiencies to Rankine efficiencies	.628	.674	.688	.7417	.7325	.668	.675
75	Percentage saving by jacketing and reheating	—	7.5	—	—	7.2	—	—
76	Steam per I. H. P. per hour in auxiliaries, lbs.	3.08	1.83	3.50	1.85	2.67	3.56	2.36
77	Steam per I. H. P. per hour in engine and auxiliaries, lbs.							
78	Steam per K. W. per hr. in engine and auxiliaries, lbs.	25.08	22.21	24.7	20.3	22.6	28.3	23.36

FEED-WATER HEATERS AND COAL.

79	Percentage of heat given by main heater to feed-water	5.8	5.8	6.3	6.2	5.3	4.7	5.5
80	Percentage of heat given by auxiliary heater	7.3	6.2	6.5	5.7	7.8	8.1	7.4
81	Percentage of heat given by economizer	.2	1.8	2.9	4.2	1.1	1.6	3.0
82	Percentage of heat given by all heaters	13.3	13.8	15.7	16.1	14.2	14.4	15.9
83	Coal per I. H. P. per hour for main engine, lbs.	1.43	1.34	1.33	1.27	1.24	1.31	1.31
84	Coal per I. H. P. per hr. for main engine and auxiliaries, lbs.	1.75	1.52	1.685	1.45	1.51	1.67	1.55
85	Coal per K. W. per hr. for main engine and auxiliaries, lbs.	2.54	2.25	2.50	2.06	2.29	2.87	2.37

more than to dry the steam. If there is any advantage in using dry and saturated steam in the L. P. cylinder over the use of wet steam, it can be obtained by the use of a separator between the cylinders. In tests 1, 3 and 7 when the reheater

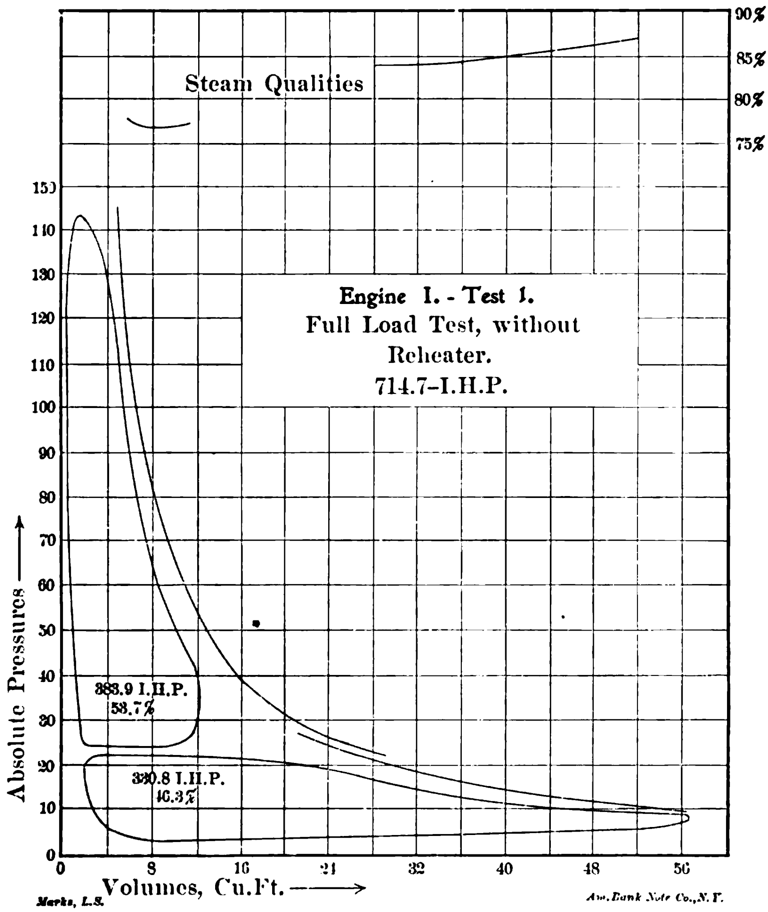


FIG. 8.

was not in use, the receiver acted as an almost perfect separator, taking away all the condensation which calculations showed to have occurred in the H. P. cylinder. If the reheater merely vaporizes the condensed steam at the expense of a prac-

tically equal quantity of high pressure steam it is not only non-effective but is also, probably, a source of actual loss, since more work could have been obtained from the total steam used if it had all gone into the H. P. cylinder. The reheater then

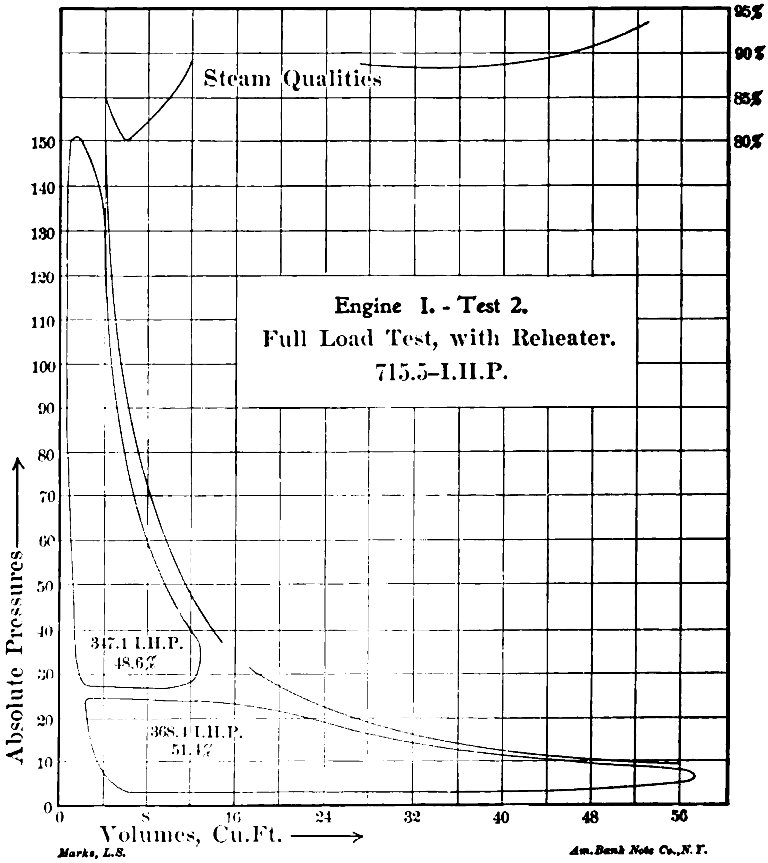


FIG. 9.

should be regarded merely as a superheating device for the steam entering the L. P. cylinder, and it may be expected to be more effective the greater the amount of superheat it gives the receiver steam. It is probable that the reheater would be more effectual if its only work were superheating, as it might

be if the wet steam exhausting from the H. P. cylinder passed through a good separator before reaching the reheater. As the reheater will have less to do when the engine is running at low loads it may be expected (see line 29) to give a higher superheat at low loads and consequently to be more effective. The

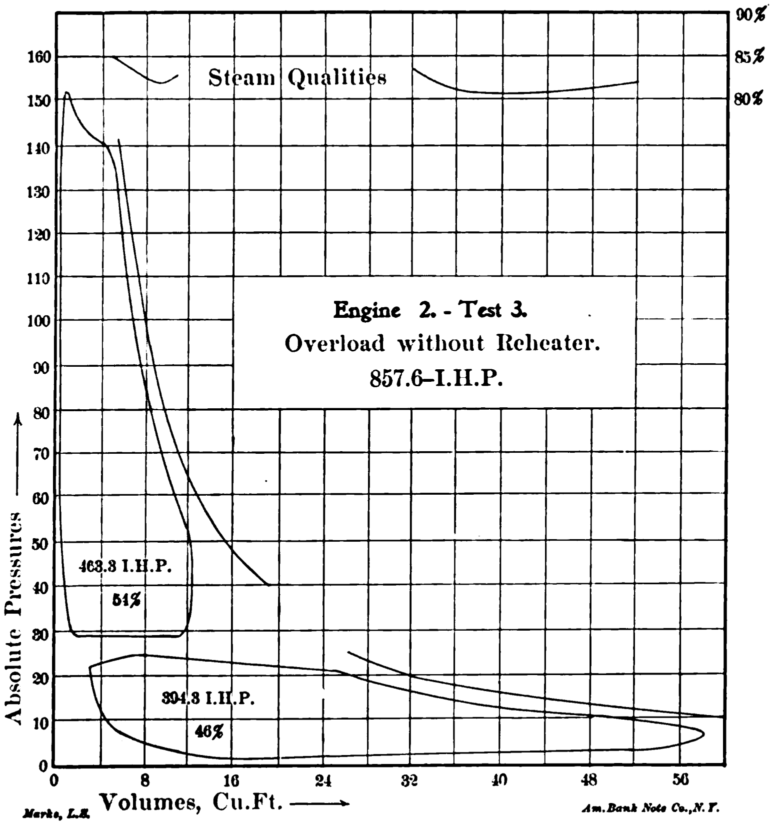


FIG. 10.

quality of the steam at cut-off in the H. P. cylinder of engine 3 for tests 5 and 7 shows that it has sufficient initial superheat and is of such size as to make the H. P. jackets of little value, so that the saving shown is due principally to the action of the reheater.

An examination of the qualities at release in the L. P. cylin-

der of engine 3 indicates that 100° superheat of the receiver steam will probably be enough to make the steam dry and saturated at release. As it is not desirable to have superheated

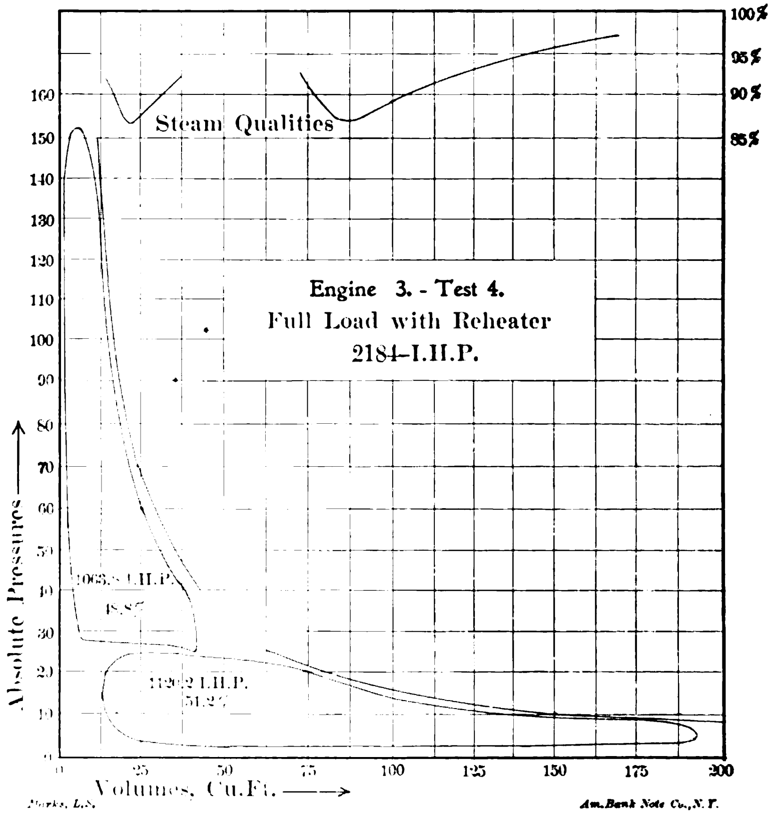


Fig. 11.

steam at release this suggests the probable desirable limit to the amount of superheat to be given by the reheater.

The Superheating.

The engines were supplied with steam from boilers fitted with superheaters designed to give from 100° to 125° superheat at the boiler when running at the rated power. The amount

of superheat at the engine (line 26) depends on the load at which the engine is running (a) because the superheat at the boiler decreases as its load is decreased and (b) because the fall of temperature in the steam pipe increases as the weight of steam passing through it diminishes. For these two reasons

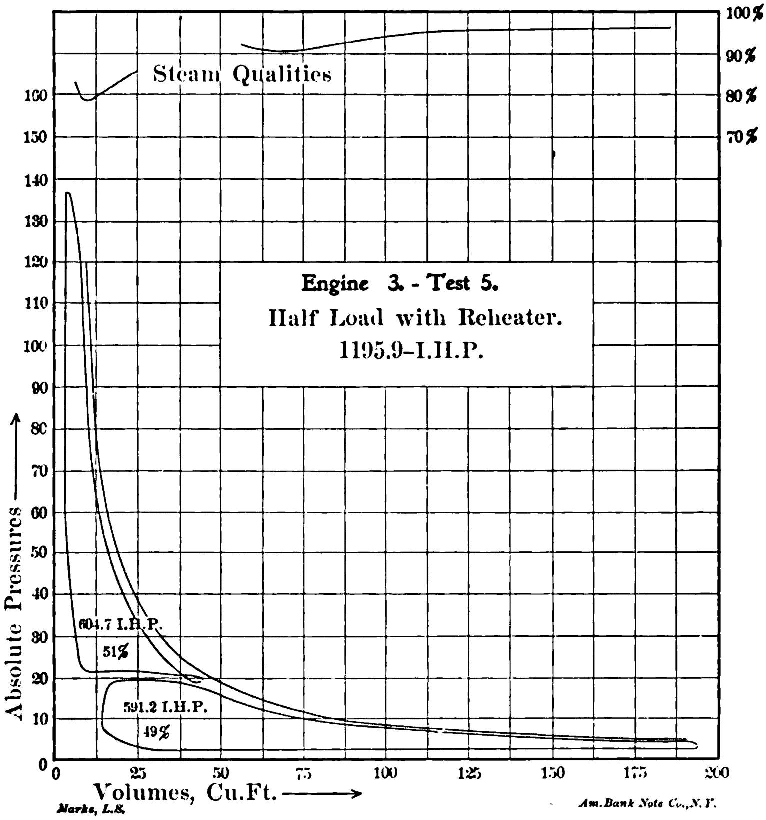


Fig. 12.

the superheat was less at low loads than at higher loads except in test 4, when two boilers were used. As the superheat going to the L. P. cylinder (line 29) when the reheaters were in use varied in the opposite way, — that is, increased with decrease of load, — these two variations tended to offset one another in their influence on the engine efficiency.

The Variation of Economy with Engine Load.

Engine 3 was tested at several loads so as to determine the effect of variation of engine load on its efficiency. The important fact is brought out (line 71) that the heat consumption per

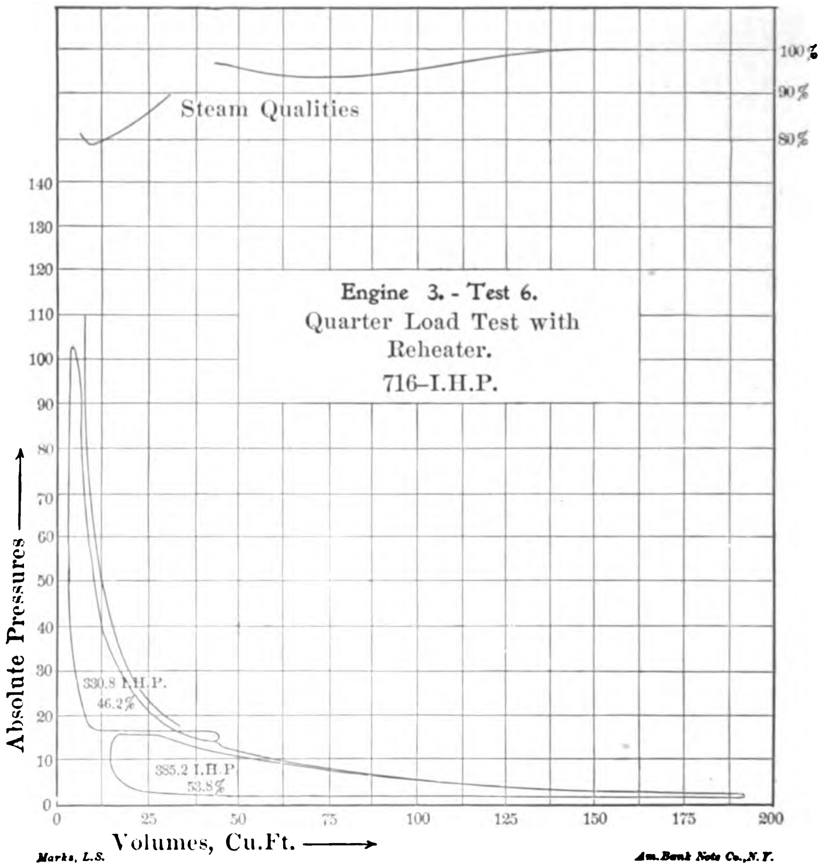


Fig. 13.

I. H. P. is practically constant through a range of load varying from one-half load to full load, and probably even to a considerable overload. This result was to be expected because the effect of superheat is to reduce the amount of heat disappearing

during admission and consequently to permit the increased expansion at low loads to occur without excessive cylinder condensation.

It is perhaps hardly necessary to emphasize the fact that the

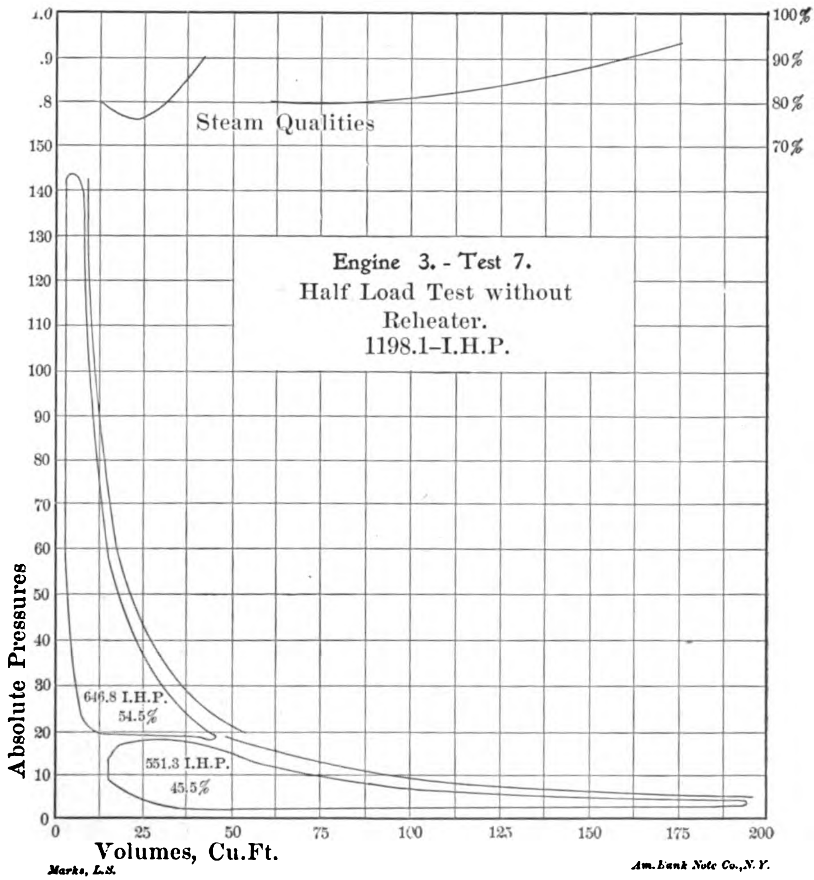


FIG. 14.

constancy of heat consumption referred to is in terms of the indicated horse-power. In engines 1 and 2 the friction horse-power is low and the mechanical efficiencies at the rated loads are high. In engine 3 the mechanical efficiency was almost certainly as high but was not ascertained. The friction horse-powers were determined by taking cards with no load on the

engine, but they really represent more than the friction of the engine proper, since they include some losses properly chargeable to the generator, — such as the brush friction, the armature windage, the bearing friction of the armature, and a low excitation of the field. Consequently the real mechanical efficiencies of the engines are somewhat higher than the quantities given in line 63 of the table.

The low friction of the engine causes the heat consumption per electrical horse-power to change a comparatively small amount as the load decreases; the heat consumption per K. W. per hour is some six or seven per cent. greater at half load than at full load.

The Radiation and Conduction Heat Losses.

In those tests where the reheater was in use, the knowledge of the exact condition of the steam entering the L. P. cylinder permitted the determination of the heat lost by radiation and conduction from the H. P. cylinder and the receiver. The total heat of the steam coming to the engine is the sum of the four following quantities: —

(1) The heat going to the L. P. cylinder.

(2) The heat equivalent of the work done in the H. P. cylinder.

(3) The heat escaping with the reheater and receiver drainage.

(4) The heat lost by radiation and conduction from the H. P. cylinder and the receiver.

The first three quantities can be calculated from the observations made on the test, and consequently the last quantity can be determined by the heat balance stated above. The radiation and conduction loss was calculated for engines 1 and 3 and was found to be $\frac{1}{2}$ to 1 per cent. of the total heat supply to the engine at full load. As the L. P. cylinder is as carefully lagged as the H. P. cylinder it appears that from 1 to $1\frac{1}{2}$ per cent. of the total heat supply to the engine at full load will be lost by external radiation and conduction. The larger percentage applies to the smaller engine.

THE "BALANCER" AS EMPLOYED IN MULTIPLE-VOLTAGE DIRECT-CURRENT SYSTEMS.

By A. E. Kennelly, Professor of Electrical Engineering.

In direct-current systems of electric power-distribution, especially for the operation of motor-driven machine tools in factories, it is desirable to install a plurality of wires and voltages, in order to operate the motors continuously and efficiently over a wide range of speeds. By the use of a three-wire system of the type used in the Edison lighting distribution, it becomes possible to operate motors over a speed-ratio range of 4 : 1, or more, If, for example, the system comprises three wires A positive, B neutral and C negative, with 500 volts between the outers A C, and 250 volts between either side and the neutral; then if the lowest speed of a shunt motor with strongest field excitation is, say, 250 r. p. m., when its armature is connected between C and B, the shunt field may be weakened so as to bring the speed up to 500 r. p. m. On reaching this speed, the armature may be transferred from the mains C B to the mains C A, with full field excitation restored, when the motor will continue to run at 500 r. p. m. Above this, the speed may be brought to a maximum of 1000 r. p. m. by weakening the field once more. The total range in speed of 4 : 1 is thus secured by a voltage variation of 2 : 1 combined with a shunt field variation of 2 : 1.

For many purposes a motor speed-range of 4 : 1 is not sufficient, and a speed-range of 12 : 1 may be required. This has been secured in some cases by the use of a four-wire system ABCD, involving three voltages. (See Figure).

Thus, between AB the voltage may be 100
- BC - - - 300
- CD - - - 200

If the field windings of the shunt motors on this system are permanently supplied from the outers AD, the armatures may be connected to any voltage between -600 and $+600$ by steps of 100. Thus

for + 600 volts, the armature may be connected with mains		AD
+ 500	- - - - - - - - -	BD
+ 400	- - - - - - - - -	AC
+ 300	- - - - - - - - -	BC
+ 200	- - - - - - - - -	CD
+ 100	- - - - - - - - -	AB
− 100	- - - - - - - - -	BA
− 200	- - - - - - - - -	DC
− 300	- - - - - - - - -	CB
− 400	- - - - - - - - -	CA
− 500	- - - - - - - - -	DB
− 600	- - - - - - - - -	DA

The motor may thus be made to operate at any speed from, say, 1200 r. p. m. in one direction on +600 volts, to 1200 r. p. m. in the opposite direction on −600 volts, by field regulation between successive connections. The speed on the lowest voltage would be 200 r. p. m., and if the range of speed control by field regulation be 2 : 1 as before, the lowest speed on this voltage would be 100 r. p. m., giving a total range of 12 : 1 in both directions.

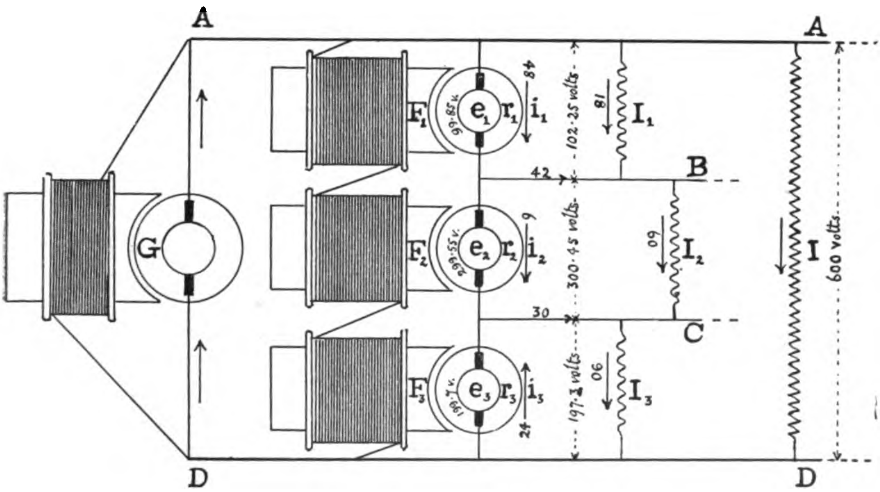
Whether the 3-wire system with a 4 : 1 range be used; or the 4-wire system with a 12 : 1 range, a plurality of generators will, in general, be needed at the source of supply, 2 for the 3-wire system, and 3 for the 4-wire system. Of recent years, the two equal voltages of a 3-wire system have been secured from one and the same D. C. generator, by giving the armature alternating-current connections in addition to the usual commutator and brushes. By this means, a neutral point can be established for the armature on the A. C. side, by the aid of choking coils, and the neutral main is connected to this neutral point.

No device has yet been introduced, however, which will successfully deliver, from one D. C. generator, three voltages, such as might serve a 4-wire system.

Rather than incur the expense of combining on one shaft a 100-volt, a 300-volt, and a 200-volt generator for the supply of a 4-wire distributing system, the plan is sometimes adopted of installing one main generator of, say, 600 volts, and supplying

the intermediate pressures from a "balancer." The balancer is a relatively small set of dynamo machines, connected in series, and having their armatures mounted on a common shaft, the number of the machines being equal to the number of different pressures to be supplied. In the case considered, the balancer would comprise three machines, one of 100 volts, one of 300 volts and one of 200 volts. The general arrangement of such a balancer is indicated in the Figure.

The shunt or compound-wound generator G supplies a steady e. m. f. E, of 600 volts, between the outer mains A D of the



CONNECTIONS OF 4-WIRE BALANCER.

system. The shunt field-magnets F_1, F_2, F_3, may also be permanently excited from these outer mains. It is understood that the bulk of the power will be delivered at full pressure E, or between the outer mains; so that most of the motors to be operated will be running at or near their highest speeds. This load is indicated by the resistance carrying the current I. The lesser and incidental loads I_1, I_2, and I_3, supplied at lower voltages, represent the motors that require to be temporarily operated at reduced speeds.

The three armatures e_1, e_2 and e_3 being mounted on, or

mechanically connected with, a common shaft, rotate synchronously. When there are no loads, I_1, I_2, I_3, the triple machine is nothing more than a composite motor, running idle and taking no more current from the outers AD than is needed to pay for the frictions of the rotating system. If, however, a load I_3 is applied, the machine e_3 acts as a generator to supply this load between its mains CD, the two other machines, e_1, e_2, serving as motors to drive it. If another load I_2 is added, e_1 acts as a motor to drive e_2 and e_3 as generators. If there be three loads I_1, I_2, I_3, the outers supply directly a current equal to the least of these three, and this part of the load comes directly upon generator G. There will always be at least one of the three machines in the balancer acting as a motor. The balancer when running idle is, therefore, a motor, and when loaded it is a motor-generator. Any one of the component machines, e_1, e_2, e_3, may be changed from a motor to a generator by reason of change in the system of loads.

The aggregate size of the balancer is usually only about 20% of that of the main generator G, the proportion depending upon the local conditions of demand for power at reduced speeds. Thus, if the generator G were of 100 K. W., the three machines forming the balancer might be respectively of say 4, 10, and 6 K. W.

It is sometimes important to predetermine the distribution of currents and pressures in such a balancer system. The rules for so doing do not seem to be found in text-books on the subject. The following formulae will be found to apply to a three-machine 4-wire balancer, and they can readily be expanded or contracted to meet the condition of any other number of wires.

In accordance with the notation of the Figure

let $E =$ the constant e. m. f. between outers AD. (volts)
" $e_1 =$ " e. m. f. generated by the armature AB. "
" $e_2 = ne_1$ " " " " " " BC. "
" $e_3 = me_1 =$ " " " " " " CD. "

n and m will usually be approximations to simple whole numbers. In the case of Fig. 1, $n = 3$, $m = 2$.

Let I_1 = the load on AB (amperes)
" I_2 = " " " BC "
" I_3 = " " " CD "
" i_1 = " current in armature no. 1 (amperes)
" i_2 = " " " " " 2 "
" i_3 = " " " " " 3 "
" r_1 = " resistance of " " 1 (ohms)
" r_2 = " " " " " 2 "
" r_3 = " " " " " 3 "
" R = $r_1 + r_2 + r_3$ or resistance of the balancer (ohms)

These resistances may be regarded as substantially constant at all loads under working conditions.

" i^1 = " current absorbed by the balancer unloaded to supply frictional losses (amperes). This friction current is assumed constant at all loads.

Then

$$i_1 = i^1 + (a-1)\,I_1 + b\,I_2 + c\,I_3 \text{ amperes}$$
$$i_2 = i^1 + a\,I_1 + (b-1)\,I_2 + c\,I_3 \quad \text{"}$$
$$i_3 + i^1 + a\,I_1 + b\,I_2 + (c-1)\,I_3 \quad \text{"}$$

where

$$a = \frac{1}{1+n+m};\quad b = \frac{n}{1+n+m};\quad c = \frac{m}{1+n+m}$$

Also $e_1 = \dfrac{E - R\,(i^1 + a\,I_1 + b\,I_2 + c\,I_3) + I_1 r_1 + I_2 r_2 + I_3 r_3}{1+n+m}$ (volts)

For example, a 4-wire system, such as shown in the figure has $e_{AB} = 100$ volts; $e_{\ C} = 300$ volts; $e_{CD} = 200$ volts, and $e_{AD} = 600$ volts. The internal resistances are $r_1 = 0.05$ ohm; $r_2 = 0.15$ ohm; $r_2 = 0.1$ ohm; $R = 0.3$ ohm. The loads are $I_1 = 18$ amperes; $I_2 = 60$ amperes; $I_3 = 90$ amperes. The no-load current of the balancer armatures is $i^1 = 3$ amperes. Required the distribution under loads.

Here $a = \frac{1}{6}$; $b = \frac{1}{2}$; $c = \frac{1}{3}$; $1 + n + m = 6$

$$i_1 = 3 - \tfrac{5}{6} \times 18 + \tfrac{1}{2} \times 60 + \tfrac{1}{3} \times 90 = +\ 48 \text{ amperes}$$
$$i_2 = 3 + \tfrac{1}{6} \times 18 - \tfrac{1}{2} \times 60 + \tfrac{1}{3} \times 90 = +\ 6 \quad \text{"}$$
$$i_3 = 3 + \tfrac{1}{6} \times 18 + \tfrac{1}{2} \times 60 - \tfrac{2}{3} \times 90 = -\ 24 \quad \text{"}$$

Here e_3 is clearly the generator, e_1 and e_2 the motors. The e. m. f. generated by machine no. 1 will be

$$e_1 = \frac{600 - 0.3(3 + \frac{1}{6} \times 18 + \frac{1}{2} \times 60 + \frac{1}{3} \times 90) + 18 \times 0.05 + 60 \times 0.15 + 90 \times 0.1}{6}$$

$$e_1 = \frac{600 - 19.8 + 18.9}{6} = \frac{599.1}{6} = 99.85 \text{ volts}$$

$e_2 = ne_1 = 3 \times 99.85 = 299.55$ volts.
$e_3 = me_1 = 2 \times 99.85 = 199.7$ "

The p. d. e_{AB} at the terminals of motor armature no. 1 will be $e_1 + i_1 r_1 = 99.85 + 48 \times 0.05 = 99.85 + 2.4 = 102.25$ volts.
$e_{BC} = e_2 + i_2 r_2 = 299.55 + 6 \times 0.15 = 299.55 + 0.9 = 300.45$ volts.
The p. d. e_{CD} at the terminals of generator armature
No. 3 will be $e_3 - i_3 r_3 = 199.7 - 24 \times 0.1 = 199.7 - 2.4 = 197.3$ "

600.00 "

The effect of applying this particular combination of loads will, therefore, be to raise the pressure on the mains AB by 2.25 volts, to raise the pressure on the mains BC by 0.45 volts, and to lower the pressure on the mains CD by 2.70 volts. The e. m. f. of the components of the balancer will be the same as at no load (99.85 volts in no. 1, or 599.1 volts in all) the drop of 0.9 volts from 600 being due to the no-load current 3 amperes through the resistance $R = 0.3$ ohms. The application of the loads will thus not alter the speed of the balancer.

The preceding proposition is of general application and may be stated in the following form: — *The speed of a symmetrical shunt balancer will not be altered by the application of any load or loads to the system within the capacity of the machines.* The pressures between the respective pairs of mains will, however, in general, be distorted by the application of the loads.

A symmetrical balancer, as the term is employed above, is one in which

$$\frac{e_1}{r_1} = \frac{e_2}{r_2} = \frac{e_3}{r_3}$$

If the balancer is dissymmetrical, *i. e.*, if the resistances of the component armatures are not proportional to their respective e. m. f's., the application of loads will, in general, alter the speed of the balancer to some extent, as will be indicated by the formulae given above.

ARCHITECTURE AS A BUSINESS.

By C. H. Blackall.

There are certain considerations which must be taken into account very seriously by whoever would make a success in the practice of architecture. It is no longer probable that a man without artistic perception and thorough training can hope to achieve eminence in the profession, but, on the other hand, it is equally well established as a fact that in order to command the confidence of business men it is absolutely essential that the architect should himself be business-like and should conduct his clients' affairs in a manner which shows him to be possessed of what we choose to call good business judgment. Such qualities are rarely attained by instruction in a school and are usually acquired as a result of years of discouraging mistakes or half successes. But some of the methods which conduce to a proper conduct of the purely business side of an architect's career can be formulated and can be readily appreciated and put in practice, if only the young beginner is willing to realize seriously the importance of the business side of his profession.

The basis of the proper conducting of any business is system. In one sense it does not matter altogether what particular system is adopted, so long as a definite scheme of operation is constantly followed which has proven itself to be efficient. It is a common mistake to suppose that a young man will necessarily grow into an acquaintance with the best practical requirements of his business. Acting on such an assumption many an architect who begins with a small practice drifts into loose ways, not only of thinking but of acting, and such habits are so easily confirmed that when the large opportunities come they often find the architect unable to handle them properly. Systematic business habits should be acquired from the very beginning of an architect's career and all his scheme and systematizing should be of such a nature that it can readily and

suddenly expand to accommodate the requirements of a business of fifty thousand or fifty million. This is perfectly possible, given the right system.

The first step, and understand I am speaking entirely from the business standpoint, is to organize the office equipment. The office itself should be as large as the architect dares to hire. A difference of a few hundred dollars a year in rental often means the difference between handling promptly and efficiently or handling clumsily and slowly the first important commission which comes in, and the space should not be cramped. The outfit of an architect must include three distinct departments. First, a vestibule, which should be fitted up attractively as evidence of the taste of the occupant and from which all signs of drawing or figuring should be eliminated. This need not be a large apartment. Eight feet square, or even sometimes smaller, will answer every purpose, and it should have a few chairs for those who wait. Then there should be a private office. This is not a luxury but a necessity, and wherever possible the private office should have a private exit. Architects' affairs are so often of a confidential nature that anything which will encourage confidence on the part of one's client and make him feel that he can speak freely, is business capital for the architect. A private office should also be attractive and artistic in its fittings. The essential furniture consists of half a dozen chairs and a flat top table not less than four by five feet. Then the rest of the premises which the architect can afford to hire should be thrown into the work room, better one single, undivided apartment, without unnecessary nooks or corners and with no more necessary ornamentation than would come in the shape of drawings of executed or projected work.

So much for the office arrangement. The office force must include, first of all, a stenographer. This again is an absolute necessity. The architect who writes his letters with his own hand now-a-days is behind the race, and a neat promptly written letter will sometimes turn the scale with a doubtful client. Next in business importance, there must be some one, even if he is the only draughtsman, who can represent the architect in

his absence so that in a business sense the architect is always on hand during business hours. The matter of more draughtsmen and their particular kind after that is not a matter of business expediency but a simple detail of how to get out the work in a satisfactory manner from an artistic and practical standpoint.

In the office equipment there are five very important features to be taken care of. They are, first, correspondence; second, drawings; third, advertisements and trade catalogues; fourth, illustrations from architectural magazines; and fifth, books. It can be stated as an inflexible rule that there should be a place for everything in an architect's office and everything should be in its place. It is further a fact that materials and documents are of no use to anyone unless they can always be found quickly and can be kept so as to be reasonably clean. For letters, my personal preference is for the Globe-Wernicke filing cabinets, each job being given a box for letters alphabetically arranged and a smaller box for specifications. These cabinets are neat and businesslike in appearance and being made in units are extremely flexible. Either this system or the vertical filing system is absolutely essential. In no case should letters be thrust into pigeon holes. With the Globe-Wernicke cabinets there is no necessity for card index, and that gives it, to my mind, an advantage over the vertical filing system.

The care of drawings is something that is generally neglected in an architect's office, and is the cause of a great deal of bother and expense, and when drawings are preserved in an untidy manner or lost and not readily located, the architect's reputation as a business man is liable to suffer. It is now the general custom to make all working drawings upon either tracing paper or tracing cloth, duplicating these by the blue print process. The best method with which the writer is familiar consists in attaching the sets of drawings to thin battens by means of small thumb screws, the battens being fitted with screw eyes on the top and hung to screw hooks arranged symmetrically on opposite sides of a series of cheap pine doors, these doors being pivoted top and bottom to swing freely in a

closet or even in one corner of the room. From five to ten sets of ordinary house plans can be thus hung on each side of a single door. The doors can be spaced six or eight inches apart and it will consequently be seen that by this system a great quantity of work can be hung in a very small space, and the fact that the drawings are suspended keeps them from curling and in practice they gather very little dust, even when not touched for a very long period. The battens are numbered and a card index of the various buildings enables one to find a set of drawings at a moment's notice. Full size drawings or drawings too large to hang on the battens can be folded away or put in cupboards, but wherever possible no drawings should be rolled or folded away.

The care of advertisements is only less essential than the proper care of letters. The architect cannot afford to throw away many of the advertisements which come to his office. As the circulars or catalogues arrive they should be looked over and a cross card index made under every heading which is likely to serve the architect in seeking for specific information regarding any article. The circulars should then be filed away either in a vertical filing system, which the writer has found very clumsy and inefficient, or, better yet, they should be attached to battens in a similar manner to what has been described for the care of drawings. These battens would be properly not over sixteen or seventeen inches long and instead of attaching them to doors they could be placed in a cabinet so the two ends would rest on light angle irons, the battens being laid close together and numbered consecutively. By this method any kind of advertising sheet or catalogue can be taken care of and kept clean and be always ready when wanted, by reference to the cross card index.

The sheets of the architectural magazines afford a valuable record of current practice, and ought never to be neglected. There are several very excellent methods of filing these sheets in suspended form analogous to that described for advertising sheets, which enable one to consult them readily and at the same time precludes the probability of the individual sheets being lost

or stolen. The plates should be classified according to subjects, and a very ample classification is desirable. The subjects could then be found quickly by the aid of a card index.

Architectural books are a business necessity. The architect who stops buying books generally stops growing and that means loss of business, so that quite aside from their artistic worth books must be regarded as essential business elements. Of course architectural books consist chiefly of pictures. The mind of the average architect becomes stored with a wealth of remembrance, but it is not enough to trust to one's memory. Every illustration in every book of the architect's library should be thoroughly catalogued on the card system and the card cases should be kept immediately adjoining the library so that every illustration can be promptly located and made available. Do not wait until your library is large before you begin to card catalogue, but take each book as you buy it and index liberally. Never use a book which is unbound. The plates become misplaced, it is impossible to index plates which are not in rigid bindings, and hence your unbound books are really of little value because of their being non-available.

The care of the correspondence in an architect's office is an important business factor. The letters should never leave the architect's desk until they are answered. It is a good rule to make their presence so objectionable as to insure a pretty prompt attention. The letter once answered, and the answer manifolded or copied into the letter press book, the letter should be at once filed in the cabinet with a brief summary in one corner stating the gist of the contents. There are several methods of caring for letters by card systems but the writer has found all of them clumsy and inefficient for private practice.

The office equipment should include a system of reminder cards, often designated as ticklers. There are a thousand little points to be attended to, a date to be kept with a possible client, a particular material to be investigated, a permit to be applied for on a certain date, a doubtful friend to be written to by some generous client, or any other matter which is likely to be put aside for the time being, may be forgotten, but which should

never be neglected. A study of the catalogues of concerns like the Library Bureau will show several ways in which these tickler cards can be made of great service and they are used far too little in architectural practice.

The architect's personal finances should be carefully watched. At least once a month, but certainly at regular intervals, a trial balance should be struck of his expenses, which should separate out the principal items of cost, including the items of salary and material. Then at corresponding periods there should be a statement made of resources, showing the amounts to come due from various jobs on hand, together with a brief summary of possibilities in the way of sketches under progress or work which has been considered but not yet definitely ordered. This enables an architect to feel reasonably sure of his expenses on the one hand and of his income of the other.

The matter of bookkeeping as relates to the accounts between owner and builder and the practical details of superintending work are subjects too large for this article. The foregoing are in a brief way the essential points which must be considered by the business architect, and the ignoring of any one of these is pretty sure to seriously impair his efficiency.

TRAIN RESISTANCE.

By C. O. Mailloux.

(Continued from the April, 1904, issue.)

B. Rolling Friction.

The phenomenon of rolling friction is illustrated by the well known action of a carriage wheel, or a pavement roller, in compressing and flattening the surface of the ground over which it is rolled. On soft ground, where this rolling action is more marked, it is found that the portions of ground passed over are pushed forward, to some extent, at the same time that they are compressed, some of the particles being usually squeezed or displaced sidewise by the compression. On a harder road surface, such as on a railroad track, the rolling action is made evident by a burnishing or polishing effect produced on the wheel treads and on the rail heads, and, in some cases, by the formation of "slivers," which become detached from the rails. The physical strains produced in the particles of matter which are rolled over require the application of additional tractive force to the vehicle, over and above what is needed to overcome the other frictional resistances. This particular tractive effort is the "rolling friction" of the vehicle. It is the force which is equal to the horizontal component of all the forces concerned in producing the physical strains just mentioned.

The rolling friction and the force required to overcome it are very small when the surfaces in rolling contact are both very hard and smooth, as in the case of a glass ball rolling on a glass plate. The slightest unevenness or irregularity in the contact surfaces is found to obstruct the rolling motion, or, in other words, to increase the "rolling friction." The explanation of this increase is quite simple. Any elevation, however slight, in either of the rolling surfaces in contact will, obviously, require the rolling object to be lifted bodily in passing over it. Any depression in these surfaces will cause the rolling object to sink

to a lower level, from which it must again be lifted bodily, just as it was in passing over an elevation. Hence, every elevation or depression, indeed every irregularity, in the surfaces which come in rolling contact, occasions some lifting of the moving (rolling) object, against its weight and the weight resting upon it. The energy consumed depends on the weight lifted, the height to which it is lifted, and the number of lifts per unit time or unit distance.

In the case of a railroad car, a very important cause of rolling friction, as we shall see, is the "hollow" caused by the yielding and bending of the rail under each wheel, which necessitates a slight, but practically continuous, lifting action. In addition to this, every irregularity in the wheel tread involves a lifting action at each revolution of the wheel; and every irregularity in the track involves a lifting action as each wheel passes over it. Thus, each irregularity, in each case, involves many lifts of various kinds; and the lifts occurring at the various wheels of a car or train supplement and succeed each other in such manner as to make the lifting action practically continuous. The weight lifted may be considered as remaining constant, in any given case. The force required to do the lifting, when the lifting action is continuous and when the weight lifted is constant, might be considered as depending on and varying with the mean height, as well as the number, of the irregularities occasioning the lifts. Now the power required to lift a car, when ascending a grade at a given speed, increases, as is well known, with the steepness or "percentage" of the grade. We might, therefore, regard *rolling friction as something which causes a "fictitious" or "spurious" grade.* The two general kinds of lifting action — "continuous" and "intermittent,"— just noted, suggest two distinct corresponding kinds of "fictitious" grades, namely, "uniform" grades and "variable" grades, the former of relatively great length and the latter of indefinite (usually small) length. This view of rolling friction gives the clearest idea of the manner in which it consumes power, and furnishes the most practical way of estimating its amount as an element of train resistance, under different conditions.

The pressure densities (*e. g.* lbs. per sq. in.) which a car wheel can produce, and the yielding effects resulting therefrom, under different conditions, play a very important part in rolling friction. The weight on the rail, per wheel, for loaded cars, is seldom under 5000 lbs.; it will usually range between 6000 lbs. and 10,000 lbs.; and it may amount to 12,000 lbs., or even more, in some cases. It is well known that both the metal of the wheel and that of the rail yield, by virtue of their elasticity, under this weight. The wheel tread is flattened, the rail head is compressed, and the whole rail itself is bent, very slightly, but appreciably, in each case. All this happens because, owing to the convexity of the wheel tread, the pressure due to the weight is concentrated over a very small space (theoretically a "line" across the rail head), thereby producing great pressure-density, at the points of contact between the wheel and the rail. It is, in fact, this very pressure-density which causes the wheel tread to sink into the rail, while bending it, and to also itself become flattened, until the theoretical "*line*" of contact has an appreciable width and becomes an "*area*" of contact. If we assume that the area of contact is one square inch, then the pressure-density must be from 5000 to 12,000 lbs. per square inch, according to the actual weight per wheel. If the area be less than one square inch the pressure will be greater, in inverse ratio. Thus, for a contact area equal to 0.1 square inch, the pressure-density due to the whole weight would be ten times greater, or from 50,000 to 120,000 lbs. per square inch. Such pressure-densities would be beyond the elastic limit for most materials; hence, as there is, normally, no permanent deformation either in the wheel tread or the rail, the area of contact must be considerably larger than 0.1 square inch if it be not as large as 1.0 square inch.

The dynamical reactions involved in rolling friction will be easily understood by considering what happens when a car wheel runs against any elevation on the track. Fig. 11 represents, diagrammatically, a car wheel moving in the direction Oa, and rolling over the forward portion RS, of the "hollow" (of purposely exaggerated size) caused by the yielding of the track

under the total weight imposed upon the rail at R. The tractive effort necessary to move the car is assumed to be applied at O, along the horizontal line Oa. This force tends to make the wheel climb the "fictitious" grade RS, which is literally "rolled down" by the wheel; and a pressure is exerted against the portion of rail RS, which pressure, for the sake of greater simplicity and clearness of analysis, may be assumed to be concentrated at a point, b, exactly as would be the case if the grade RS were replaced (Fig. 12) by an "obstructing" particle, S, of matter placed on a level track, and coming in contact with the wheel, at the same point, b, as in Fig. 11. We may note, in passing, that while Fig. 11 is typical of a "uniform" fictitious grade, Fig. 12 is typical of a "variable" one. The former represents a "continuous" obstruction while the latter typifies an "intermittent" one. The reactions being essentially the same in both cases, they may both be analyzed and discussed together. They differ only in details which need cause no confusion. The pressure along the line Ob, in Fig. 12 (corresponding to what would be the *mean* pressure in Fig. 11) is always the resultant of two forces, one due to the weight (W) acting vertically downward along the line OR, and the other due to the moving force acting along the line Oa, as already stated. Since the lines of action, OR and Oa, of these two forces, both pass through the axis (O) of the car wheel, it follows that the line of resultant pressure, Ob, will also, of necessity, always pass through O. The angle a, between the line OR of pressure on the rail at R (due to weight), and the line Ob of pressure on the "obstruction" at S

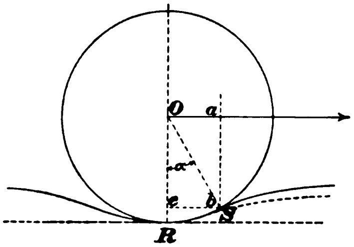


FIG. 11.

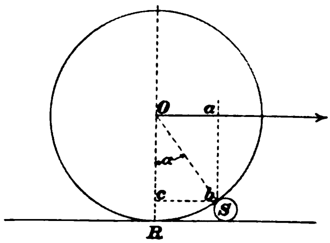


FIG. 12.

(due to both weight and tractive force), depends primarily upon the *height* of the obstruction, or the height (Rc) of the point b above the point R of the rail. When the obstruction is smaller, as shown by the dotted line in Fig. 11, or when a larger particle (like S, in Fig. 12), yields under the pressure exerted upon it, the distance (Rc) of the point of contact b, from the rail will, obviously, be reduced, as can be seen in Fig. 13, which shows the angle *a* for two particles of different sizes. While the angle in the vector diagram of forces (Fig. 14) depends upon the size of the "obstruction" typified by S, the *magnitude* of the forces, or the *size* of the *diagram*, depends upon the physical properties (elasticity, resistance, etc.) of this obstruction, or the extent to which it will *yield* under pressure. If we represent by Ob, in Fig. 14, the pressure exerted at *b*, at a given, very minute, interval of time after the wheel has come into contact with S, then the line Oa will represent the tractive force required to produce this pressure, while the line Oc will represent the amount of weight which has become displaced from the line OR to the line *ab* in Fig. 11. By the time that the total pressure at b has increased from Ob to the amounts relatively indicated by the distances Ob_1, Ob_2, the tractive effort will have increased to the relative values Oa_1‘ Oa_2; and while the downward pressure upon S has *increased* to the relative values Oc_1, Oc_2, the pressure at R, due to weight, will have *decreased by an equal amount*. If the obstruction S, or the "grade" RS, be rigid and unyielding, the forces will further increase, very rapidly, until the downward component of the pressure along Ob (*i. e.* Ob_n) is such that Oc_n represents the whole weight (W) bearing upon *b*. This means simply that the tractive effort will

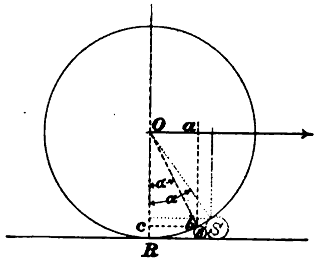


FIG. 13.

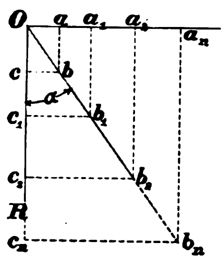


FIG. 14.

increase until the whole weight (W) is lifted from the rail at R (Fig. 12) and has become transferred to the point b, at which time the wheel will begin to climb over the "obstruction." If, however, S (or RS) is elastic and begins to yield as soon as pressure is exerted upon it, the vector diagram is not so simple, because, owing to the successive reductions of the distance Rc (Fig. 12) and, therefore, of the angle a, as the obstruction yields more and more, the position of the line of pressure Ob, will not remain the same, but will constantly change. The lines Ob, Ob_1, Ob_2 —— Ob_6, in Fig. 15, indicate, approximately, various stages of the change in the direction of the line of pressure Ob, or in the angle a, in the hypothetical case of an obstruction of any kind which continues to yield under the pressure applied at b until it is completely flattened out to zero thickness.

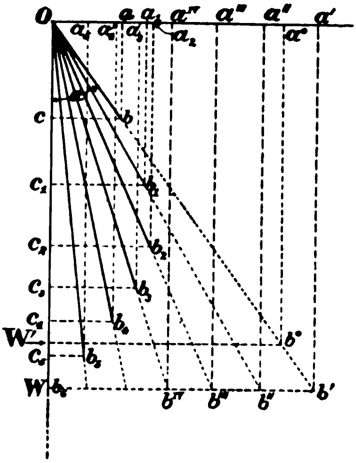


FIG. 15.

The distance Oa, in this case, may be taken as representing the extent to which the tractive effort has to be increased (from zero) before the obstruction begins to yield at all, the ratio of tractive effort to pressure produced, or weight displaced, remaining constant. Beyond this point, while the angle a changes from WOb to WOb_1, to WOb_2, etc., the ratio of tractive force to pressure diminishes. The tractive effort, as can be seen from the diagram, attains a maximum value (Oa_2 in this case), and then decreases, becoming zero when the point b is exactly under the wheel, in the line OR (Fig. 12). (It is clear that when the whole weight W is exerting a downward pressure upon the point b, the horizontal component (*i e.* the tractive effort) must become equal to zero.) If the line OW in Fig. 15 represents the total weight (W), then, in the case of an *unyielding* particle of size S, the pressure would continue to increase along the line

Ob prolonged, the tractive effort in the meantime increasing also, at constant ratio, until the whole weight (W) is displaced from R to b, the values of pressure and tractive efforts being then as represented by the lines Ob′ and Oa′ in Fig. 15. As soon as the lifting action begins the distance Rc will thereby be reduced, and the angle a will decrease rapidly to zero. The vertical component of pressure at b (now equal to the whole weight) will, obviously, remain constant (= OW); hence, while the angle a decreases from WOb′ to WOb″, to WOb‴, etc., the tractive effort will decrease from its maximum value, Oa′, to Oa″, to Oa‴; and so on to zero. The maximum value (Oa′) occurs, as we have seen, at the very instant when the wheel is being lifted off the rail at R.

It is easily seen, from Fig. 12, that the resisting force, g, to be overcome to make the wheel climb over S by turning around b as a fulcrum, has a leverage equal to bc, $= x$, and a moment equal to the product of this distance by the total weight (W) to be lifted in climbing, or $g = Wx$. The moving force, F, (= Oa′) applied at O, will exert a leverage equal to ab, = Oc, = y, and its amount, in order to give a moment (Fy) equal to that of the resisting force will be $F = W\dfrac{x}{y}$,

(1) where $\dfrac{x}{y}$, as can be readily seen from the diagram (Fig. 11), is equal to the trigonometrical tangent of the angle a, comprised between the point of contact, b, and the vertical line RcO. We could therefore write:

$$F = W \tan a, \qquad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \qquad (1a).$$

Since $\dfrac{Rc}{RO}$ = versin $a = 1 - \cos a$, and since $\tan a = \dfrac{\sin a}{\cos a} = \dfrac{\sin a}{1 - \text{versin } a}$, it is evident that (taking OR = r and Rc = z) we will also have

$$F = \frac{x}{r - z} W \qquad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \qquad (2)$$

Substituting for x its value, $x = \sqrt{r^2 - y^2}$, we have

$$F = \frac{\sqrt{r^2 - y^2}}{r - z} W.$$

Expressing y in terms of r, we have, finally,

$$F = \frac{\sqrt{z\,(2r - z)}}{r - z}\,W \quad . \quad . \quad . \quad (3)$$

where F = tractive force per wheel, in pounds.

It is obvious from these equations, as well as from the diagrams, that the force F, required to move a given weight (W) over a particle S or a fictitious grade RS, will be smaller for a large wheel than for a small wheel, and will increase, in all cases with the height of the obstruction.

Although these equations are based upon the reactions occurring at a single wheel in special cases of rolling resistance they still apply in the case of cars or trains having any number of wheels, and for all kinds of rolling resistance. The formulae for the resistance due to rolling friction, as given in most text-books relating to the subject, have precisely the form of equation (2). The term z is sometimes omitted, the resulting error being quite small and usually negligible, when the numerical value of z is small, as is the case in railroad traction. We can see, from Fig. 11, that this omission amounts to the same thing as replacing the *tangent* of a, $= \frac{x}{r - z}$, by the *sine* of a, $= \frac{x}{r}$, in the equations, since, when we make z = versin a = o, we have

$$\tan a = \frac{\sin a}{1 - \text{versin } a} = \frac{\sin a}{1 - 0} = \sin a$$

which is approximately correct only when the angle a is very small. Remembering that equations (1a) and (2) are equivalent forms, we could also, by analogy, when z is neglected, write

$$F = \frac{x}{r}\,W = W \sin a \quad . \quad . \quad . \quad . \quad . \quad . \quad (2a)$$

When we take W = 2000 lbs., in these equations, F will represent *pounds per ton.*

The real measure of the force expended in overcoming rolling friction is a mean value of F in every case.

It is evident from the equations, especially (1a) and (2a), that the value of F, being a function of the angle "a", will be constant only when that angle is constant. When the angle is variable these equations are correct only for instantaneous values.

The mean value, F_m, is, in every case, equal to the distance-integral of the instantaneous values, F, divided by the distance (X) comprised between the limits of integration, or

$$F_m = \frac{1}{X}\int_{x'}^{x''} F\,dx$$

In the case of a continuous rolling resistance (Fig. 11), where the angle a is practically constant, the instantaneous values will be substantially the same as the mean value. In the case of an intermittent obstruction (Fig. 12), however, the angle a and the instantaneous values will quickly range from zero to a certain maximum and back again to zero, and there is no evident relation between any instantaneous value and the mean value. We can still use the same equations, nevertheless, for expressing mean values, even in the case of intermittent resistances, provided we select a *mean* or "effective" value of the angle a, such that its tangent or its sine, according to the particular form used, will satisfy the conditions. This has to be done, in fact, in practice, for another reason which we will now consider.

Referring again to Figs. 12 and 13, we can see clearly that the pressure-density at the point b would quickly become very great, owing to the very small area of the contact, and that the elastic limit would be reached, even for the strongest materials, after a relatively small proportion only of the total weight (W) became transferred from the line OR to the line ab. The material will be crushed at its points of contact with the wheel and with the rail (where the pressure density is greatest) at the same time that some compression occurs in the mass of the particle, the result being that the angle a is materially decreased, and that the same weight displacement is thereby made to exert a still greater pressure-density without causing any increase in the tractive force. The further increase in pressure-density causes further yielding by both compression and crushing, and a consequent further decrease in the angle a until the obstruction has been flattened by compression and crushing to a layer which can yield no further. Even then, however, the wheel will not have to be lifted a distance equal to the full thickness (Rc) of

the compressed layer, because it is, so to speak, partially embedded in the wheel tread and the track, which both yield slightly to make room for it to some extent, very much in the same way (though to a very much smaller degree, of course) as in the case of a rubber-tired vehicle rolling over a small pebble on an asphalt pavement. The "effective" thickness will therefore be less than the "actual" thickness of the layer, and, consequently, the angle a, and the value of F, will be still further decreased. The value of F, especially at the beginning of the process of lifting, may be also reduced in another way, namely, by the reaction due to the compression of the wheel tread and of the rail, at the point R. This reaction will, obviously, "*help to lift*" the wheel, or it will virtually *reduce its weight*, at least during the earlier stages of the lifting process. If, in Fig. 15, the vertical line WW′ represent the reaction or lifting force due to elasticity, the weight to be lifted will be $OW - WW' = OW'$, and, consequently, the maximum value of the tractive force required will be Oa° instead of Oa′. The decrease of the angle a, in the manner already explained, will be such that, by the time the whole weight (OW) is being lifted, the line of pressure will have changed to some line like Ob″ or Ob‴, so that the tractive force will not increase but, on the contrary, will have decreased. It is seen, from the equations, (2), (3), that F will be smaller when W is diminished. It would seem, therefore, as if these equations would be correct only when we take "effective" values, lower than real values, for the angle a (on which the "lifting distance", eR, depends), and for the weight lifted (W). As to the angle a, its "effective" value and the values of the factors (x, z,) depending upon it, must of necessity, be hypothetical, when they are not conventional ones. As to the weight (W), it is more convenient to take actual values and make allowance in some other way for the lifting actions due to resilience just referred to. We may regard the compression of the wheel tread and the depression of the track at the point R (Fig. 11) as having caused the storage of a certain amount of energy which is partially "recoverable" and whose "force-factor" has a horizontal component acting in the same direction

and in the same line as Oa (Fig. 11). We can readily see, from Fig. 15, that if Oa′ represents the total tractive force required to move the whole weight (OW), (the line of pressure being along Ob′), a lifting force such as WW′ will have a horizontal component equal to Wb′ − W′b° = Oa′ − Oa°. Consequently, although the total tractive effort is equal to Oa′, only the portion Oa° will consume additional power. The net result is therefore exactly the same as was obtained on the assumption that the lifting force caused a reduction in weight.

These considerations suffice to show the great complexity of the conditions influencing "a", and the difficulty of obtaining its "actual" value. As a matter of fact, the only practical way now known of determining the "effective" or "hypothetical" value of "a" is to first measure F under different conditions by suitable means, such as by a traction dynamometer, and to substitute its value in the equations. When F and W are both known, we have, respectively,

from (1) and (2), $\frac{F}{W} = \tan a = \frac{x}{r - z}$ . . . . (4)

and from (1a) and (2a), $\frac{F}{W} = \sin a = \frac{x}{r}$ . . . . (4a)

In every case r, the radius of the car wheel, is also known. Hence, the only unknown quantities are x and z in (4) and x in (4a). On referring to a table of trigonometrical functions, we readily find "a" and also the values of these quantities. When z is neglected, as is the case in (2a) and (4a) it is no longer necessary to obtain the value of "a" itself, since x, its sine, which is the only unknown quantity, is easily obtained, thus: —

$$x = \frac{Fr}{W} \qquad (5a)$$

The quantity x has been called, by some writers, the "coefficient of rolling friction," notwithstanding the fact that it represents a *distance* (= cb in Fig. 11) and that it is not a *ratio-factor*, like the coefficient of sliding friction.

This quantity has been generally used, by the earlier investigators of rolling friction (Coulomb, Dupuit, Morin, etc.), and it

is still mentioned in text books, as the measure of rolling friction or the criterion of comparison between different kinds and states of rolling friction. The results of Coulomb's experiments with wheels of iron or steel rolling on rails of iron or steel are given, in a recent text book, in terms of a value of x ("effective"), ranging from .007 to .02 inch. This method is not in harmony with modern ideas and notations, and, notwithstanding the fact of its having been used by many distinguished men, it is unsatisfactory and obsolete; and it should give way to some more logical method, such as that of measuring rolling friction in terms of an equivalent or effective "fictitious grade," as already stated.

Fig. 16 shows, diagrammatically, a wheel ascending a grade, RS. It is well known that the coefficient of rise of the grade is equal to either the sine or the tangent of the angle (β) of inclination of the track, according to whether we measure the rise (LS) in terms of the actual length of track run over (RS) or of the horizontal projection thereof ($=$ RL). Thus, taking $\beta = 2°$ we would have

$$\frac{SL}{RS} = \sin\beta = \sin 2° = .03490, \text{ in one case, or}$$

$$\frac{SL}{RL} = \text{Tan}\,\beta = \text{Tan}\,2° = .03492, \text{ in the other.}$$

These coefficients, when multiplied by 100, to express their values in percentage, represent *percentages of grade*, which are 3.49 % and 3.492 %, respectively. (These figures show that the error due to taking sine values instead of tangent values in the various equations given, is negligibly small. Even for a 10 % grade ($\beta = 5° 42' 38''$) the sine is still only 0.5 % (exactly) less than the tangent). Treating the grade in Fig. 16, as if it were a "continuous obstruction" and constructing the vector diagram of the forces involved, we find that the vector diagram Oabc is exactly the same in Fig. 16, as in Figs. 11, 12, etc., when Oa is the tractive effort applied at O, or when it is the horizontal component of a tractive force, Oa', applied in some other direction, such as along a line parallel with the track. We note, moreover, that, in the vector diagram Oa' bR, obtained with the

force Oa′ itself, the line of total pressure Ob, and the angle α, both being independent of Oa, remain exactly the same as in the diagram Oabc. Now, it is easily seen (Fig. 16), and proved, by reference to either of these two vector diagrams, that the angle β is equal to the angle α. Hence it follows, at once, that: *the angle a is the same as the angle of the "fictitious grade" and its tangent or its sine is the coefficient of rise for that grade.* This coefficient, when expressed as a percentage figure, gives the percentage of the fictitious grade. It is a *true coefficient*, perfectly analogous to the coefficient of sliding friction, as can be seen from equations (1a) and (2a). We can now appreciate the fact that the "quantity x," taken alone, is insufficient and may be misleading, as a measure or means of comparison of rolling friction; for, as we see clearly from (4a), the same value of x, with different values of the radius of the car wheel (r) will give widely different values for the coefficient of rise and, consequently, for the percentage of the "fictitious grade," on which the power consumed depends. The values of x obtained from Coulomb's experiments, just mentioned, are therefore useless as a clue to the tractive effort or the power required to overcome rolling friction in any other case than the original experiments themselves.

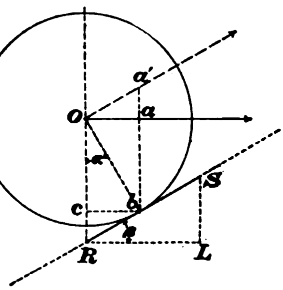


FIG. 16.

We will now consider briefly the principal kinds of rolling friction.

(1) The rolling friction due to mangling or crushing effects is illustrated in a striking manner by the great increase in train resistance caused by "sand" on the track, other examples being furnished by rust, dust, grit, mud, snow, ice, etc. It is well known that the train resistance is lowest, in a given case, either during or after a shower, the explanation being that the rails are then washed clean of sand, dust, dirt, etc. The difference in train resistance is obviously much more pronounced

on street railways, where the tracks are normally much less clean than on steam railroads. A summer shower thus benefits street railway companies, for the time being, in two ways: by increasing the number of passengers; and by decreasing the energy consumption per passenger carried.

The "obstruction," in all cases of this class of rolling friction, is a complex one, produced by the aggregation of a very large number of relatively small particles of matter, constituting "elemental" obstructions of the "intermittent" kind. If the obstructing particles were all alike, in form, dimensions, mechanical resistance, etc., and if their distribution on the rails were perfectly uniform, their resultant effect could be considered the same as that produced by a "continuous" obstruction, *i. e.* by a constant "fictitious grade"; and the tractive force, F, required to overcome this "obstruction," would be practically constant. Such is never the case, however. There is an incessant variation in the elemental obstructions themselves, and also in their disposition on the rail, whereby the resistance offered to the *first* wheel of the train or car is rendered very irregular. The passage of the first wheel causes many of the particles to be pushed or brushed aside both before and after crushing them, those which remain on the rail being finely crushed and compressed to a thinner and more uniform layer than that presented to the wheel in the first place. The same process, substantially, is repeated as each succeeding wheel of the train or car passes over the same portion of track. It is obvious that the tractive force (F), under such conditions, must vary considerably at any one wheel, more especially the first wheel. We will get an idea of the kind of "fictitious grade" which each wheel has to overcome, if we replace the straight line RS, in Fig. 16, by a wavy line. It is presumable (although we still have no actual proof), that this line has smaller waves, if not fewer waves, or is more nearly straight, and also that the mean angle (β) is smaller, for each succeeding wheel, until, after a given number of wheels have passed, the angle, and the fictitious grade, have both practically vanished.

THE GREEK DORIC ORDER.

By Walter Dana Swan.

To make a complete study of architectural forms they should be treated from the historical and archeological point of view as well as from the architect's standpoint, as constructive elements in the design of buildings. There is a third and no less important conception of them. This is that of the student beginning his study of principles and methods. He is learning to observe, to analyze, to think constructively and to prepare himself for logical design with the materials of his time and country.

From the many historical forms then, there are picked out for his study those which answer his earliest needs, which combine the best principles of architectural pure design — structural logic and promise of enduring vitality and use, and — as he is learning to draw as well as to design and build — those which best and simplest show the principles of draughtsmanship. Some of these selected forms have more of certain of the above qualities than the others have, but each has something for illustrating active principles if not always adding to the designer's vocabulary. Among the historical forms which satisfy these conditions certain of the Greek and Roman Orders fill all the above requirements.

Let us see then why it is that in addition to the so called Tuscan Order already considered, the Greek Doric and Ionic and the Roman Corinthian Orders, are par excellence the best possible architectural elements for a beginner to study. This should be after he has become familiar with the general principles of building, has learned to distinguish between lintel and arch construction, and has had practice in design involving each.

The orders are details of lintel construction and as in all study and analysis, mass is considered before detail, it seems most essential that the study of the composition of buildings

themselves, however simple, should be considered previous to their parts. The order is a detail of the portico and colonnade so that it seems necessary to consider the use of those elements simultaneously with their detail. But the order is also something more than the detail of a form of buildings. It is a system of structural design, and as system underlies all forms of successful achievement; ones early acquaintance with it strengthens the ideas of the meaning of *design*.

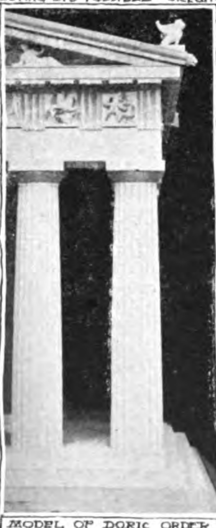
As stated in a previous article the Greek Doric form is so closely identified with a particular sort of Greek temple that it rightly belongs nowhere else. Why then do we concern ourselves with this order, drawing it out in projection and perspective, learning it by memory, analyzing it in model and photograph? It will play no part in our future practice, which will be largely with modern forms of construction. We may never be obliged to design a portico or colonnade. We may live and practice in a locality where the proper material for a column is not obtainable. Where then is the practical benefit to us from our care devoted to this form? It is because it completely satisfies the first of our requirements for the study of the elements for the beginner, it exemplifies the best principles of architectural pure design — balance, rhythm and harmony. These require fuller explanation but it is only necessary to state now that they exist. Familiarity with examples which display them is much better in the early stages than precepts concerning them.

The taste and judgment cultivated by contact with these fine things, the feeling for the right form of the right size in the right place, comes gradually as a reward for all the time and care which the faithful beginner gives to such details as this Greek Doric Order, developed as found in the Parthenon at Athens.

The historical study of this form shows us the spirit which lead the Greeks by developing this order through a long period, to perfect the work of the past to meet new conditions, and is that not to be one of our aims as practitioners along with the inventions of new forms and new material to meet new conditions?

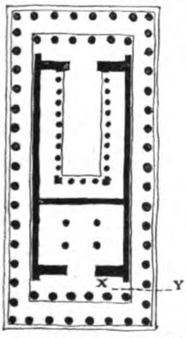
LOGGIA DESIGNED BY MESSRS SHEPLEY, RUTAN & COOLIDGE SHOWING LOGICAL USE OF DORIC FRIEZE AND SUGGESTING ITS POSSIBLE ORIGIN

RESTORATION OF PARTHENON (ACCORDING TO BOETTICHER)

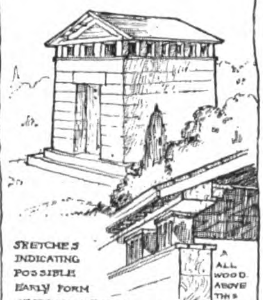


MODEL OF DORIC ORDER OF THE PARTHENON, ATHENS

PARTHENON MODEL SHOWING ROOF

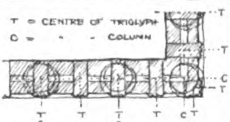


SKETCH PLAN OF PARTHENON



SKETCHES INDICATING POSSIBLE EARLY FORM OF TRIGLYPH FRIEZE

DIFFERENT DORIC ORDERS SHOWING HOW THE CONSTRUCTIVE LENGTH OF STONES OF ARCHITRAVE, AND NOT FORMULÆ INFLUENCED PROPORTIONS



SECTION PLAN SHOWING RELATION OF COLUMNS TO TRIGLYPHS

W D S

Let us consider as briefly as we well can, this Doric order referred to from the standpoint of the beginner, first noticing its different parts constructively, — its organic design or the effect on our intelligence — then its qualities of pure design or its pleasing effect upon our sense of vision, and finally practice our hand and eye in drawing it out accurately, never losing sight of it as a solid form and not merely a combination of lines.

The column lacks base, or rather that member is identified with the stylobate or base of the whole structure; the columns are fluted; the capital is of the same general idea as the Tuscan with the transition from the round to the square. The architrave is formed in its depth from outside to inside, of as many stones as are necessary to make it strong enough, and the span of the lintel or architrave between two columns of course depends upon the material employed as well as upon the triglyph frieze, as we shall see later.

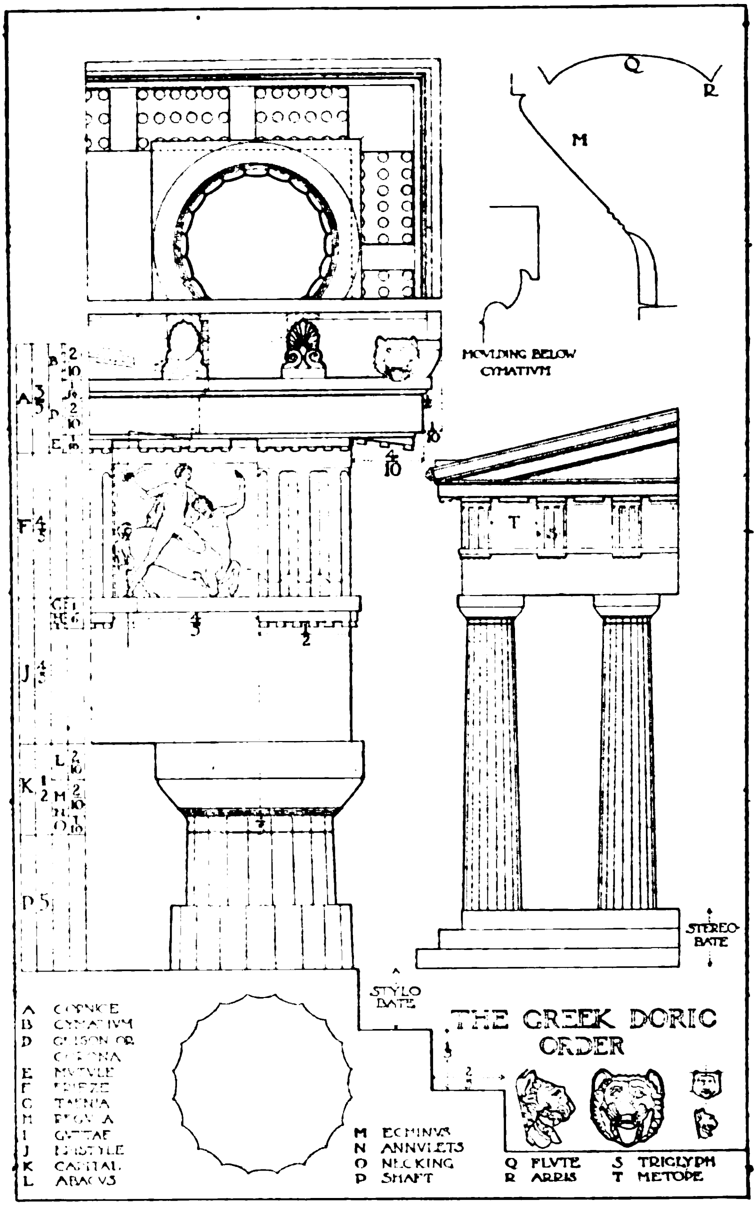
The frieze is built upon the flat top of the architrave, with the triglyph blocks bearing the principle load.

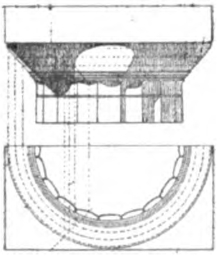
We are studying archeology only in so far as it serves our purposes as architectural students and the origin of the Doric order is more or less an archeological question but we do want to know that the Doric frieze is practically a non-constructive feature and is so undoubtedly because the entablature is of wooden origin, while the column was probably of stone in the earliest days of any rudimentary Doric construction. The first temples were covered with wooden roofs. This seems undeniable. There has been a great deal of academic discussion about the origin of the order and it deserves especial consideration which lack of space here prohibits.

We saw the logic of the frieze in the Tuscan order, and we shall see its meaning as an element of design in this case, but not constructively so as in the case of the other fully developed Doric members.

What seems the most reasonable theory yet advanced with regard to the triglyphs, is perhaps that of * M. Guadet who

* Guadet. Elements et Theorie de l'Architecture.

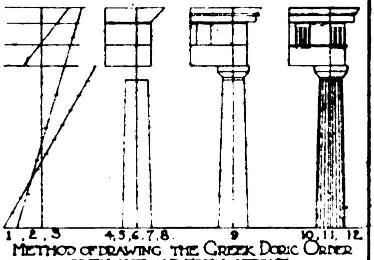

THE GREEK DORIC ORDER
MOVLDING BELOW CYMATIVM
STYLOBATE
STEREOBATE
A CORNICE
B CYMATIVM
D GEISON OR CORONA
E MVTVLE
F FRIEZE
G TAENIA
H REGVLA
I GVTTAE
J EPISTYLE
K CAPITAL
L ABACVS
M ECHINVS
N ANNVLETS
O NECKING
P SHAFT
Q FLVTE
R ARRIS
S TRIGLYPH
T METOPE



SHADE AND SHADOW ON CAPITAL

FIND SHADE OF ECHINUS ①, SHADOW OF ABACUS ON ECHINUS ②, AND SHADOW OF LOWEST ANNULET AND ARRISES IN FLUTES BY MEANS OF SECTIONS LIKE "A"

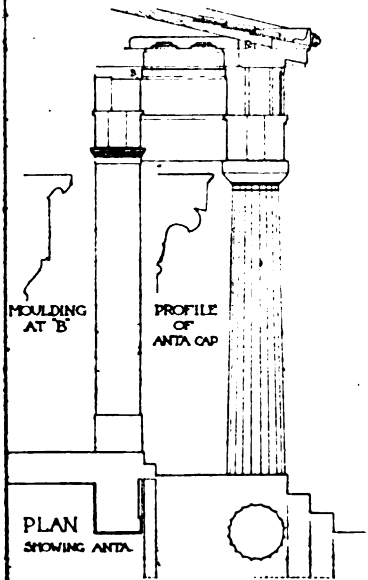
THE GREEK DORIC ORDER

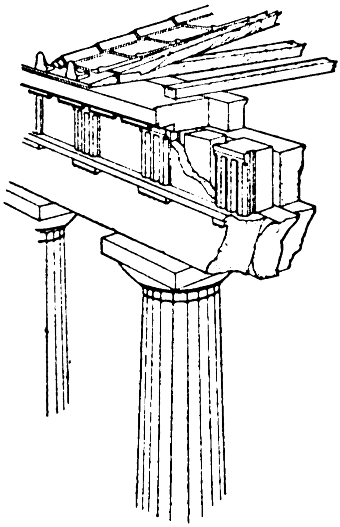


METHOD OF DRAWING THE GREEK DORIC ORDER GIVEN AXIS AND TOTAL HEIGHT

① DIVIDE TOTAL HEIGHT (COLUMN + ENTABLATURE) INTO 7 PARTS. ENTABLATURE = $\frac{2}{7}$ ② DIVIDE ENTABLATURE INTO 11 PARTS AND LAY OFF 4·4·3. ③ DIVIDE COLUMN INTO 11 PARTS, 1 PART = $\frac{1}{2}$ DIAM. ④ LAY OFF FACE OF EPISTYLE, $\frac{1}{2}$ DIAM. FROM AXIS ⑤ LAY OFF LOWER DIAMETER, $\frac{1}{2}$ DIAM. FROM AXIS ⑥ LAY OFF HEIGHT OF CAPITAL, $\frac{1}{2}$ DIAMETER ⑦ LAY OFF UPPER DIAMETER = HEIGHT OF EPISTYLE ⑧ LAY OFF BOTTOM OF CORONA, $\frac{1}{2}$ DIAM FROM TOP OF ENTABLATURE. FIND END OF CYMATIUM BY A LINE AT 45° ⑨ LAY OFF TRIGLYPHS AND METOPES ⑩ LAY OFF SMALLER DIMENSIONS USING TENTHS OF A DIAMETER. ⑪ LAY OUT FLUTES, USING A QUARTER PLAN AT BASE AND NECKING; DIVIDE QUARTER CIRCLE INTO 10 PARTS 1 PART EQUALS $\frac{1}{2}$ OF A FLUTE. ⑫ DRAW GUTTAE TRIGLYPHS AND RINGS ON CAPITAL.

GENERAL SECTION





PERSPECTIVE SECTION SHOWING CONSTRUCTION

believes that its early use was such as is indicated in the sketch on page 285 and exemplified in the modern design shown on the same page. This it seems to me is one of the points in Doric construction which is vital enough to add to our working vocabulary.

To go on with our description — the projecting corona which covers the wall is cut with the drip to throw off the water and its underside pitches down and away from the vertical wall for the same reason. Then the gutter or cymatium* B is obvious, while the lion's head forms the spout for water from the pitch roof, and the antifixae or ornaments cover the ends of ridges of the roof tile.

As a study in pure design notice in the first place the contrast of the solid base or stylobate with the upward movement of the columns with their sharp vertical channels or flutes, the mass of the architrave broad, horizontal and reposeful contrasting with this vertical movement. Observe the recall of the columns in the short triglyphs in the frieze and the projection of the cornice, —its shadow binding all below it into a unit.

Notice how the frieze, never absolutely essential constructively, seems necessary to give proportion to the whole upper part of the building. Study all this in the mass of the temple itself first, then follow it into the detail of each part. See how the column's flutes are arranged and designed of such a section and in such number as to be best related to what comes above, how they are bound together by the incisions of the necking, how the line of support of the square abacus starts from the very bottom of the shaft and is carried beautifully to the bottom of the abacus — yes almost to the architrave itself. Observe the line of the echinus, as wonderfully simple as it is difficult to draw. Note how the architrave is connected with the frieze by means of the guttae below the triglyph. See how the triglyphs are fluted to recall the column below but with angular incisions to suit their rectangular form. Both of these relations with members below give unity to the design.

See how the corner triglyph strengthens the appearance of

* See double page diagram. Drawn by A. E. Hoyle, '04.

this part of the entablature in the most logical way, and that the triglyph and the metope each have a capital as well as the column. This is important to remember from observation of the cast as is also the fact that in Doric design the interval of the triglyphs in the frieze is the measure set for the spacing of the columns, for with the exception of the corner triglyphs they are all located over the centre of each column and midway between these. The position of the architrave or epistyle with relation to the capital is to be noted in this developed type, for earlier and later its position varied.

Then see how the bottom line of the corona, harsh otherwise, is broken into a delightful softness by the mutules which in their turn are helped in the same way by the hanging guttae. These members of the cornice may or may not be the results of original wood construction but they are perfect in their present relation in the design of this order.

There is little in the two diagrams of the Doric Order here published which seems to call for explanation. Comparison with the photographs, or still better with the actual models, will show the relation of such parts as are not understood in the projections of the diagram. It is to be remembered that these dimensions are to serve only to fix in the memory this general form of the order as a point of departure for its more particular study and appreciation, and for use in the elementary discipline of draughtsmanship. The diagrams are never to be used as formulae.

The different examples of the Doric Order with their varying details but with the same underlying system which developed patiently gave them the perfect beauty of the Parthenon, should be studied in the various published * monographs on the Greek

* Buhlmann. Die Architektur des Classischen Alterthums etc.

Cockerell: "Temples at Aegina and Bassae."

Hittorf and Zanth: "Architecture de la Sicile."

Koldewey und Puchstein: Die Griechischen tempel in Unteritalien und Sicilien.

Laloux: Olympia.

Penrose: "Principles of Athenian Architecture."

Stuart & Revett: "The Antiquities of Athens."

Also "The Unedited Antiquities of Attica."

temples. These are to be found in all the best architectural libraries.

Greek Doric roof construction is decidedly hypothetical, some authorities believing that little or no wood was used in the developed Doric temple form. It is generally conceded that the Greeks were not familiar with the truss and its principles.

Two possible varieties of rafter treatment are shown in the diagram. Terra cotta roof tiles were used in connection with the early limestone temples of Magna Graecia, but with the highly developed marble temples of Athens and vicinity, all visible features were of Pentellic marble. M. Guadet thinks that in the Parthenon even the roof construction as well as the covering was of marble:—that the walls were carried either from the floors or from above lintels over the columns to support stones of the longest spans.

It is hard to restrict the study of the Doric forms to the order merely, for the temples themselves with all their wonderful refinements and proportional relations of both form and color call for and repay our closest investigation, but space forbids further consideration here. The materials have been mentioned and their influence on the construction and the design cannot be insisted upon too strongly. The difference must be noticed between the longer spans which the strong Pentellic marble gives in the Parthenon and the shorter unsupported length which the cautious builders at Paestum gave their limestone lintels.

In the diagram the anta perhaps calls for a word or two. * "It was a portion of the wall projected to answer to the column which took the other end of the lintel. It was to have a capital to give it expression but it was to be treated in a manner perfectly distinct from the column — in no way imitating it." The anta given here illustrates the principle but is. shown in connection with a smaller column in front of it and not with the column shown in the general section. The section shown here is taken on the line X–Y in the sketch plan on page 285.

* H. H. Statham. Architecture for General Readers, p. 73.

In drawing the order in the conventional projections what will most tax the beginner will be the profiles of the mouldings and the forms of the ornaments and sculpture, but if the positions of various points in the outlines are first obtained, then the measures or dimensions of the forms are indicated accurately, the shape, which is the third consideration, and desired result, will not be so difficult. That indicates the sequence to be followed. The analysis of the form, of the lion's head is indicated at a small scale in the right hand plate. The axis defines the position of the form. Certain points in its outline show the measures of the projection of the form, and its outline, with the shades and shadows which follow in the rendering, determine its shape. This indicates the process followed in all architectural drawing.

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Editorial.

We take pleasure in announcing the election of the following active members to the Board of the Journal: Walter C. Durfee, 2nd, *Mechanical;* Percy L. Moses, '06, *Electrical;* L. A. Andrus, '06, *Civil.*

Graduate Notes.

E. S. Harrison, '04, is with the American Diesel Engine Co. and has been representing the firm at their installation in the Tyrolean Alps at the St. Louis exposition.

E. N. Hunting, '03, is superintendent of construction and engineer on reinforced concrete construction for Robert A. Cummings, Pittsburg.

F. E. Frothingham, '96, is local manager of the Whatcom County Railway & Light Co. for Stone & Webster.

A. G. Franks, '04, is studying coal mining, handling and transportation at the New River Coal Mines in W. Va.

K. E. Adams, '03, has left the Blake Pump Works and has returned to the Walworth Mfg. Co. of Boston.

K. Sherburne, '03, has transferred from the Schenectady works of the General Electric Co. to the new plant in Lynn. He is engaged in steam turbine work.

A. L. Haskell, '04, is in the steam turbine department of the General Electric Co. at Lynn.

D. W. Armistead, '98, has left the Allen–Chalmers Co. His present address is 6702 Alden St, Pittsburg.

Aldrich Durant, '03, is with Westinghouse, Church, Kerr & Co., at Pittsburg. He had charge of the Westinghouse–Parsons steam turbine exhibit at the St. Louis Exposition.

Thayer Lindsley, '04, editor-in-chief of the Engineering Journal in 1903, is with the New York Rapid Transit Commission, in the Division of the Tunnel under the East River.

A. Tyng, '04, and L. Ross, '03, have appointments in the University as Austin Teaching Fellows in Engineering.

A. D. Wilt, '03, has contributed an article on "How to Introduce High Speed Steel into a Factory" to the Engineering Magazine. It was published in the September number.

F. R. Bauer, '04, is employed in drilling operations in the Indian Territory oil field. His address is Bartlesville, Ind. Territory.

T. R. Clark, '04, is engaged in production of oil in the Perma Oil Fields.

W. T. Piper, '03, is with U. S. Steel Co. at Lorain, Ohio. His address is 625 12th St., South Lorain, Ohio.

E. O. McKelvy, '02, is New England representative of a Pittsburg refractory material company. His address is 234 McKees Place, Pittsburg, Pa.

Architectural Notes.

While the articles on the Classic Orders published in the JOURNAL occasionally seem to be more for the benefit of the beginners than the practitioner, there is really much for the latter's consideration in the principles involved. He may think that he has escaped from the teacher's ideals and precepts and shakes his head over what he calls the folly of theories but he must certainly feel the force in these ideas lately published in one of the architectural magazines by a busy successful practitioner. "How often are we really trying to build our client's house rather than our own monument? Yet the one is architecture, even if the man and his house be vulgar, and the other is not architecture even though it rival the glories of Greece or Rome in its splendor of line and proportion. At least if architecture does not mean the honest use of materials in frankly, and if possible, beautifully, fitting the need of our fellow men, then I do not know what it means. . . . It is this lack of analysis, this *unthinking* use of architectural forms and precedents, that is standing in the way of architecture and the allied arts that hang upon its skirts. . . . If we can square ourselves with the eternal verities of architecture, not architectural style; if we can think in solids, not in line; if we will realize that stone is stone and wood wood and not misuse them; if we can realize that it lies with us to guide both the public and the craftsman to a simple expression of their life in the building they must of necessity build; then we may indeed hope for a new renascence that shall be both reasonable and purposeful. 'To thine own self be true, and it must follow, as the night the day, thou canst not then be false to any man.'"

The interesting article published in the last issue on "The

Problem of an Architect in Remodelling New York City," was written by J. A. Gade, '96, A, one of the class of two which was first graduated from the then new Department of Architecture in the Lawrence Scientific School. He was an assistant in the Department after graduation, then in the office of Messrs. McKim, Mead and White and is now a member of the firm of Foster, Gade & Graham in New York City. The photographs shown in the article were of work done by that firm.

A. H. Blevins, '98, A, is in practice in the firm of Newhall and Blevins in Boston. This firm has designed recently two important apartment houses in Cambridge.

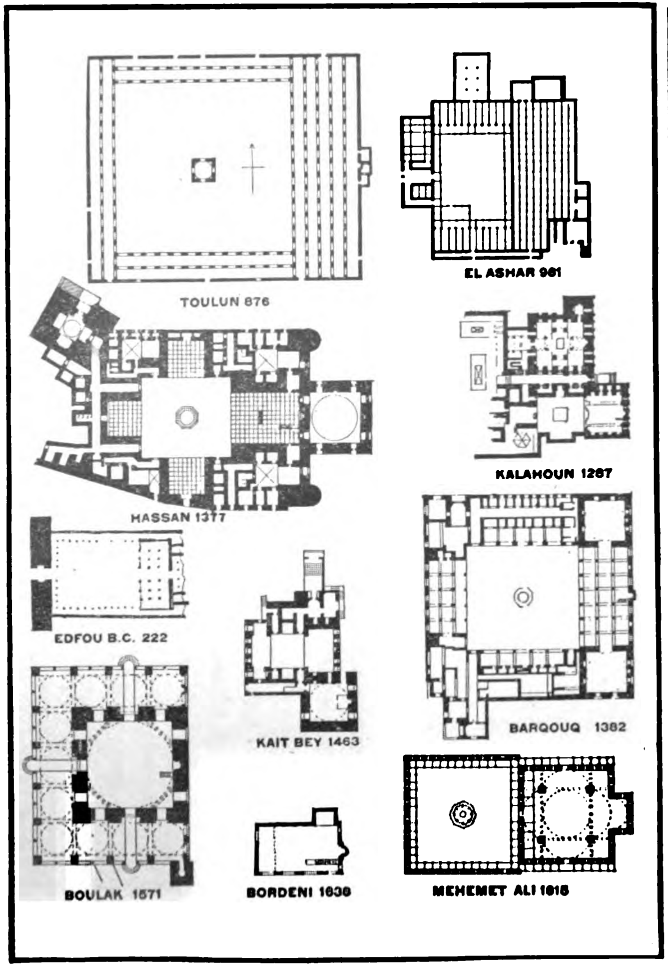
A. E. Hoyle, 1904, A, and F. L. Clark, 1901, A, are at present in the office of G. F. Newton in Boston.

E. T. Putnam, '01, has passed the entrance examinations for the Ecole des Beaux Arts in Paris and is at present working in that city.

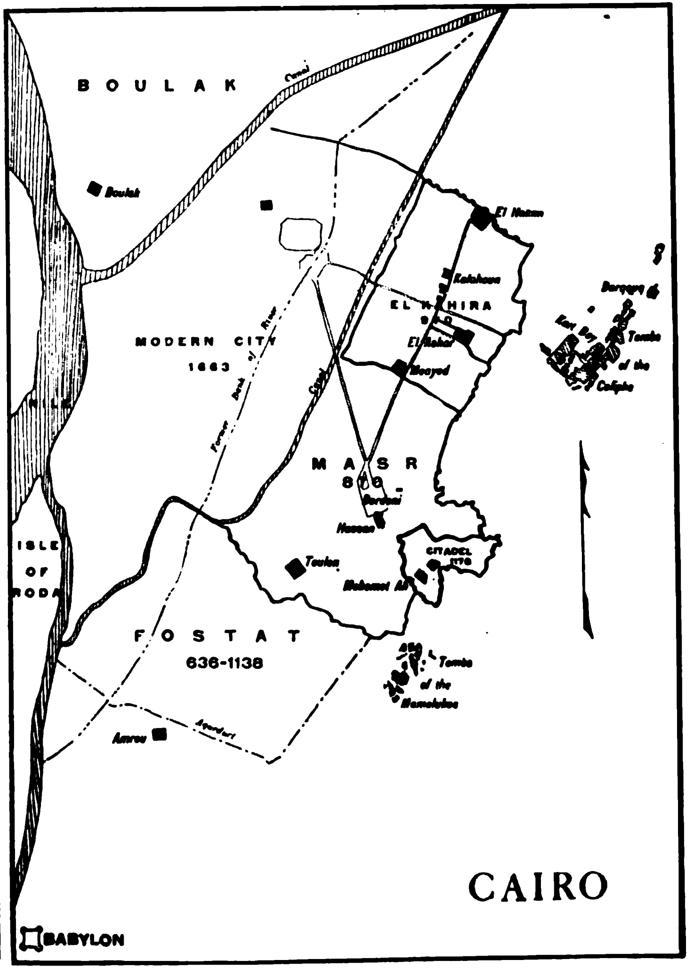
The competition for the Nelson Robinson Jr. Fellowship will be keener than ever before this year, for it seems probable that there will be four candidates for this distinction. It is hoped that the name of the winner with some mention of his successful design may be published in the next issue of this Journal.

Mr. C. H. Blackall who has so kindly contributed to this number the timely article on that important phase of the architectural profession, its business methods, recently gave, under the auspices of the Pen and Brush Club, a lecture on Theatres. He is a noted authority on that subject.

H. D. Whitfield, '98, A, of the firm of Whitfield and King in New York, the winners of the recent competition for the club house for the Society of Engineers in that city has offered to the Pen and Brush Club, of which he was at one time president, a bronze medal to be competed for annually by the club members. It is to be held in perpetuity and is to be awarded to the winner of a competition which shall be arranged by the head of the Department of Architecture. The name of the winner of each year is to be engraved on the back of the medal and the award is to be made as near Class Day as practicable.



PLANS, AT DIFFERENT SCALES.



OUTLINE MAP.

622 Hegira	632 MAHOMET dies at Medina (30 years)
"The Four First CALIPHS" (Successors)	
632 ABU BEKR, father-in-law	634 OMAR, general
644 OTHMAN, general (Ommiad)	656 ALI, son-in-law (Fatima) (Abbas, uncle)
EGYPT 638 Amrou conquers Egypt Mosque at Fostat, 642	662 OMMIAD CALIPHS Damascus (90 years) Mosques at Jerusalem, 637, 691 Mosque at Damascus, 705 700 Musa conquers Africa 711 Tarik, Battle of Xeres "Roderick, the last of the Goths" 732 Charles Martel, Battle of Tours 750 OMMIAD CALIPHS Cordova (500 years)
750 *Abbassides* (120 years) 870 *Toulonides* (Turcoman mercenaries) Mosque of Toulun, 876. 970 *Fatimites* (El Moezz) (200 years) Cairo Mosque El Ashar, 981 Mosque El Hakim, 1000	750 ABBASSIDE CALIPHS Bagdad (500 years) 810 Haroun-al-Raschid Tombs at Bagdad
1170 *Ayoubites* (Saladin, Seljukian) (80 years) Citadel	1055 Seljukian Turks take Bagdad 1075 Seljukians take Iconium 1096 Seljukians take Damascus
Mameluke Sultans 1250 *Baharites* (Turkish slaves) (132 years) Mosque of Kalahoun, 1287 Mosque of Hassan, 1377	1250 Mongols conquer Bagdad 1299 Ottoman Turks take Iconium Mosques at Broussa, 1389
1382 *Borghites* (Circassian slaves) (135 years) Mosque of Barqouq, 1382 Mosque of Moayed, 1412 Mosque of Kait Bey, 1463	1453 Ottomans take Constantinople
1517 Osman Selim conquers Egypt *Mameluke Governors* (300 years) Mosque at Boulak, 1571 Bordeni Mosque, 1638 1806 *Mehemet Ali* Mosque in Citadel, 1815.	1453 TURKISH CALIPHS Sulimanieh Mosque, 1550 Validé Mosque, 1665 Laleli Mosque, 1760

NOTE.

The Historical Table prefixed to this paper gives at the top the date of the Hegira, of the death of Mahomet, and of the accession of the "Four First Caliphs" who succeeded him at Medina.

Below are given the names and dates of the successive dynasties which have held sway in Egypt from that time to this, in nominal subjection to the Ommiad, Abbasside, and Turkish Caliphs, who have inherited, or assumed, the spiritual authority of the founders. The table contains the names of the principal sultans and of the more important of the Cairo mosques and their plans are given, and their position in the city shown, in Plate I.

In a second column are given the principal contemporaneous events of Mohammedan history outside of Egypt, so far, at least, as they concern the immediate object of this paper. It marks the duration of the Ommiad, Abbasside, and Turkish caliphates.

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SARACENIC ARCHITECTURE.

By Professor William R. Ware, '52.

I.

Mahomet was an Arab chief, and the Arabs were barbarous tribes of the desert with no art, and no materials for art, except for the art of poetry. Painting, sculpture and architecture were alike unknown to them. In Egypt they came in contact with the Byzantine Empire, and with what remained of the civilization of the Roman Empire and of the Greek Empire of Alexander, and, what was more important, with what remained of the old Egyptian civilization, an influence which already had produced marked effects not only upon the Romans and the Greeks, but upon the Jewish colonists who had settled in Alexandria. Meanwhile the peculiarly mystical turn of the Egyptian mind had affected both philosophy and religion, and to this day it affects the philosophy and religion of all Christian countries.

The Hegira, or flight of Mahomet from Mecca to Medina, took place in the year 622, and he died in 632, ten years later. The first Caliphs, the successors, of Mahomet, were his father-in-law, Abu Bekr, his generals, Omar and Othman, and his son-in-law, Ali. They are known in history as the Four First Caliphs.

Note. — The substance of this paper is taken from a lecture given at the Metropolitan Museum, in New York, in February, 1899, and again in Cambridge, before the *Pen and Brush Club*, in March, 1904.

Some of the figures in Plates XI and XII are taken from M. Gayet's "*Art Arabe*," a volume to which I am indebted also for much information. The rest are taken mostly from photographs, and from sketches made in Egypt and Asia Minor in 1890.

They established and maintained the caliphate at Medina for thirty years. It was the caliph Omar who, with his General Amrou, conquered Egypt and burned the Alexandrian library, or is said to have done so; the next, Othman, belonged to the Ommiad family, of Medina. The fourth caliph was Ali, the husband of Mahomet's only child Fatima, and the disputes which followed his accession have divided the Mohammedan world to this day between the Sunnites, or orthodox Mohammedans, and the Shiites, or Fatimites, the followers of Ali. The Shiites, though adhering to the only descendants of the prophet, are held to be heretics and dissenters.

At the end of the thirty years, that is to say in the year 662, the Ommiads, of the family of Othman, murdered Ali and his two sons Hassan and Hussein, and removed the caliphate to Damascus, where it remained for ninety years. It is rather singular that although Hassan and Hussein belonged to the hated sect of the Shiites, they are held in the greatest veneration by the orthodox Sunnites. They are the most revered of Mohammedan saints and martyrs, and the day of their death is everywhere celebrated with tumultuous demonstrations of grief. Even in London, the Mohammedan sailors make the docks resound with their lamentations. The martyrs Hassan and Hussein are known in Cairo as the Hosaneyn. By the unbelieving inhabitants of East London, they are called Hobson and Jobson.

In 750, the descendants of Mahomet's uncle, Abbas, came to the front, and in their turn murdered at Damascus all the Ommiads but two. One of these escaped to Southern Arabia, where he founded an Ommiad Caliphate which lasted 800 years. The other, Abd-er-Rahman, a little boy, fled to Spain and founded the caliphate of Cordova. At the same time the Abbassides moved the orthodox caliphate from Damascus to Bagdad, where they reigned for five hundred years until, in 1250, they were conquered by the Mongols, or Moguls, and took refuge in Cairo, where the caliphate remained until the sixteenth century, when the Turks took possession and carried it to Constantinople.

Meanwhile Musa, a Mohammedan general of the Ommiads, conquered the north of Africa. This conquest is about the only important event with which to mark the year 700. In 711, Tarik crossed the Straits of Gibraltar, which takes its name from him, Gebel-el-Tarik, the Hill of Tarik, and conquered Roderick, "the Last of the Goths," in the battle of Xeres. In 732, spreading into France, just a century after the death of Mahomet, the Arabs were defeated by Charles Martel in the battle of Tours. Thus, it is held, was France, and in fact the whole of Europe, rescued from Mohammedan control and perhaps from the Mohammedan religion.

Finally, the Turks, in two bodies, seized Syria and Asia Minor. The Seljukian Turks who maintained themselves at Iconium in Lycaonia during the twelfth and thirteenth centuries, were followed at the beginning of the fourteenth century by the Ottoman Turks, who established their capital at Broussa in Bithynia, fifty or sixty miles south of Constantinople. They took Constantinople in 1453, and fifty years later conquered Egypt, and the Turkish Sultan assumed the title of caliph. The principal monuments of the Turks are their mosques at Constantinople.

We will here consider only the Mohammedan architecture which was the best claim to be called Saracenic, that of Egypt. It was not only the earliest, but, being the first, it gave tone and character to the architecture of every country which the Mohammedans conquered. Everything in Spain, Persia and even India seems to have obtained its main inspiration from the architecture of Egypt.

In the year 638 Amrou, the general of the caliph Omar, conquered Egypt, and in 642 founded a town near the old Roman fortress called Babylon, which stood on the eastern bank of the Nile, just below Memphis, at the head of the Delta. He then proceeded to the conquest of Alexandria, but as he was striking his tent, he noticed that a couple of doves were building their nest on the top of it, and ordered that they should not be disturbed. On his return from Alexandria the tent was still standing. "Fostat" is the Arabic word for "tent," and he called his town Fostat, the town of the tent. (Plate I.)

The mosque he built there is the oldest in Cairo. But it has been rebuilt so often, that the present Mosque of Amrou shows few traces of the original structure. (Plate II).

It constantly happens that the earliest remaining monuments of any civilization are already of mature character. The earliest Greek temples date back to about 666 B. C., but they have every mark of being the last of a long series. It is the same with the old Egyptian temples. The earliest examples which remain are obviously a very late product. They also are the last members of a series, the early examples of which have disappeared. So it is here. For two hundred and fifty years after the Hegira the history of Mohammedan architecture is a blank, and what happened can only be guessed. The earliest Egyptian monument which still exists undamaged is the Mosque of Toulun, built in the year 876. (Plate III.)

The Arabs themselves, at least in the beginning, seem to have had little relish for the arts of design, and the development of Mohammedan architecture is apparently due, in the main, to a people of another race. These were the Turks. They, like the Arabs, were a nomadic people, with no art and with even less literature, but they had, as they have shown in many fields, a strenuous disposition, — they were of a masterful turn of mind; they had a sincere appreciation of what was good in the art of design and they had a passion for building. The history of Mohammedan architecture is chiefly the history not of the Arabs' work, nor of work done for the Arabs, but of the work done for the Turks by the races whom they conquered. They made their appearance in Egypt in various guise, as slaves, as mercenaries, as allies, or as conquerors, and in whatever character they appeared they manifested the tyrannical disposition which enabled them to control the government, and the appreciation of art which turns a potentate into a patron. Both ran in their blood.

What is called Saracenic architecture is then, even in Egypt, not that of the Saracens, but that which was patronized by the Turks. Here, as afterwards in Constantinople and in India, they employed native workmen to build and adorn their monu-

ments. But who were these artists? If we knew the history of the first two hundred and fifty years we should be better able to answer this question, but the artists employed in Egypt were apparently the ancient inhabitants of the country, the Copts. The derivation of this name is somewhat disputed. It may come from the town of Coptos, an important Christian city under the Romans. But Copt seems to be "Gypt"; at any rate, the Copts were the old Egyptians. There is another derivation based on the fact that they were Jacobites; "c" "b" "t" spells Copt, very nearly. There was an early Christian father, a Syrian, named Jacob Bar-Dai. He and his followers, called Jacobites, were denounced as heretics by the Council of Calcedon in 415, but the Egyptian Christians held to the Jacobite doctrine, and may possibly have got their name from it. This doctrine, which thus had an oriental rather than a Greek origin, just suited the mystical turn of the Egyptian mind. It held that it was absolutely impossible that in the person of the Saviour the human and the divine should have been united, for the divine cannot possibly have anything in common with the human. This is what is called the Monophysite doctrine,—the theory of only one nature. There are still 600,000 Copts in Egypt who to this day profess the Monophysite heresy. Their religious services are still conducted in the Coptic language, which, however, they no more understand than do most Catholics understand the Latin prayers of their church. If you enter a Coptic church you hear the Coptic language and listen to the last echoes of the ancient Egyptian tongue.

Now these Copts were the artisans and artists whom the Arabians, and afterwards the Turks, employed. It is recorded that the first mosque at Mecca was built by Copts who were captured in the Red Sea, with all their building materials, while on their way to build a church in Abysinnia. By the time of Toulun, in the ninth century, the new style was apparently so perfected that it only needed encouragement to produce works of great splendor. This Toulun was a Turk, one of a band of mercenaries who had been brought from Bagdad. He rose from being steward of the palace to the position of supreme ruler,

very much as had happened in France, a hundred years before, when Pepin, Mayor of the Palace, founded the Carlovingian dynasty. Toulun obtained complete control of all Egypt, established the dynasty of the Toulunides and built himself a new mosque at Fostat. Like the mosque of Amrou, which it resembles in plan, it consists mainly of a large court much like the courts of the old Egyptian temples at Luxor and Edfou. (Plate I.)

This central court was called the *Sahn*; the arcades around it, the *Liwan*; the niche showing the direction of Mecca, the *Mihrab* or *Kibleh*; the pulpit, alongside, the *Mimber*; the desk, holding the Koran, the *Kursi*; the gallery or raised platform from which the clerk repeated the lessons was the *Dikkeh*; and the fountain in the middle of the Sahn, the *Sebil.* These features were in time much modified, and some finally disappeared. Under the Baharite Mamelukes the Sahn was much contracted, and the arcades of the Liwan were replaced by great vaulted niches. Finally, in Constantinople the Ottoman Turks covered the Sahn or central court with a dome. Some of the latest and smallest Egyptian mosques, such as the beautiful Bordeni mosque, had only the niche and the pulpit, the Mihrab and the Mimber.

The story told of the mosque of Toulun is that it had been the habit to get columns by pulling down Coptic churches, but that the Coptic architect whom the conqueror wanted to employ refused to have any part in such desecration, and said that if he could have a free hand he would build the finest mosque in the world and not use a single column. This is the mosque of Toulun.

The descendants of Toulun reigned one hundred years. Meanwhile, the heretical Shiites had established themselves in power at Tunis and in the year 970 their general, named Moezz, conquered Egypt and established the dynasty of the Fatimites. This is about the only appearance of the Fatimites in history, except in Persia. These took possession of Fostat and built near by the new town of Cairo. (Plate I.) This was at first a sort of royal suburb. The story here is that they had

consulted the astrologers and had strung a string of bells which was to be rung at the propitious moment, giving notice to the workmen to begin work simultaneously. Unfortunately, while they were waiting for their signal a raven passing by lighted on the string, the bells rang and the work was begun, when to their consternation the people found that the planet Mars was just in the ascendant. Mars was considered a planet of evil, but the officers in charge, with much presence of mind, proclaimed that the omen was a happy one, and that the town should be called the victorious. It thus received the name El Kahira, the victorious, from which the modern names of "Le Caire" and "Cairo" are derived.

The years of the Fatimites were among the most splendid in history. Their Cairo was the city of the Arabian Nights. The contemporary and apparently authentic accounts of their display of wealth are almost beyond belief. What remains at this day are only some beautiful private houses and some half ruined mosques, of which the largest is the mosque El Ashar, "the Resplendent" (Plate IV), now used for the University, and the mosque, built by the fanatical Sultan El Hakim, now occupied by the Arabic Museum.

Meanwhile, the Turks were again in evidence, this time as allies. The Seljukian Turks had established themselves in Syria with headquarters at Damascus. The Crusaders undertook to conquer Egypt, and the Fatimite Sultan made an alliance with the Turks at Damascus, who sent Saladin to his assistance, who burned the city of Fostat lest it should fall into the hands of the Crusaders. Its remains are now known as Old Cairo. The modern Cairo consists of the Fatimite suburb El Kahira and the district called Misr, which lies between El Kahira and a Citadel which Saladin built towards the south and by the aid of which, like a Roman of old, he held in subjection the people he had rescued. (Plate I.) Thus the dynasty of Saladin and his descendants replaced the Fatimites. It is called the dynasty of the Ayoubites, from his father, a Seljukian Turk of Damascus named Ayoub. The principal architectural monument of Saladin is this fortress. (Plate IX.)

When, in the year 1250, the Mongols conquered Bagdad, the Abbasside caliphs, as has been said, fled to Egypt and nominally resumed the sway. But they had no political power. The government was seized by successive dynasties of slaves, or Mamelukes. Here again the Turks are in the ascendant, for the first Mamelukes were Turkish. We have met the Turks, first as mercenaries, then as grasping allies. Now they appear as slaves and the Mameluke Sultans of the first dynasty reigned for more than two hundred years. They were called Baharites, being quartered near the Bahr, or river. Two of the most famous mosques were built by them, the Mosque of Sultan Kalahoun (Plate V) and the Mosque of Sultan Hassan (Plate VI). The earlier mosques had been quite plain on the outside, but from the time of the Baharite Mamelukes their buildings began to take on some exterior architectural treatment.

The Mosque of Kalahoun is not merely a mosque. It is also a Muristan, or hospital, and large buildings are connected with it. The Mosque of Sultan Hassan also is really a Medresa, or school, a building ten stories high, attached to which is the tomb of the founder. This is covered by a dome, a construction which was originally used in Egypt only for tombs.

The Turkish Mamelukes were succeeded by a dynasty of Circassian slaves, who are known as the Borghite Mamelukes, or those from the Fort. They built the Mosque of Moayed near the southern gate of the city, much after the plan of the Mosque of Toulun, and splendidly adorned it with marbles. (Plate VIII.) They built also the so-called Tombs of the Caliphs outside the eastern gate, of which the most noticeable are the mosque-tombs of Barqouq (Plate VII) and of Kait Bey (Plate IX). A similar collection of tombs, mostly anonymous, beyond the citadel of Saladin on the south, is called, with better reason, the Tombs of the Mamelukes.

Finally, the Turks appeared in Egypt as conquerors. The Ottomans took Constantinople in 1453, and early in the next century conquered Egypt but continued the Mamelukes in power. Their principal architectural works are the mosques at Broussa in Bithynia and those built in Constantinople in imi-

tation of the church of St. Sophia. About a hundred years ago the Egyptian ruler Mehemet Ali murdered all the Mamelukes within the Citadel of Saladin and built there a mosque after the Constantinople pattern. (Plate IX.)

Meanwhile, although the Mameluke governors had not done very much building in Cairo, two of their mosques are of special interest, — the mosque at Boulak, a suburb of Cairo near the river (Plate X), and the little Bordeni mosque, near the Citadel (Plate X). The Boulak mosque, and a copy of it within the precincts of the University, is covered with a dome, but it is in plan and arrangement entirely unlike the domed mosques at Constantinople, and both in design and in architectural treatment it is one of the most original and charming of buildings. The Bordeni mosque, built about seventy years later, is very beautiful in detail, but without structural features. It is merely an oblong room with a niche and a pulpit, the Mihrab and Mimber, but no Sahn; that is to say, no court.

II.

But the quality of Mohammedan architecture lies not wholly in the disposition of the plans and the composition of the masses within and without. The novelty, ingenuity and elegance of the structural and decorative details are equally admirable, and some of them present peculiarities of unusual interest.

The most conspicuous of these is the so-called honeycomb, or stalactite, work, a singular device which is used on the under-side of all sorts of projections, almost to the exclusion of mouldings. Capitals, cornices, string-courses, brackets, arches and vaults, domes and the pendentives that support them, are entirely composed of little niches piled one above another in an endless variety of fantastic combinations. Sometimes these are rectilinear, and resemble a broken honeycomb; sometimes they are bounded by curved surfaces. It is not difficult to devise theories as to the origin of this unique feature. But since for the first two hundred and fifty years after the Hegira we have no Mohammedan buildings, and in the oldest that now

survive the distinctive features of the style are, as has been said, already fully formed, all hypotheses in regard to its source are equally difficult of verification. Everybody is free to choose for himself the one that seems to him to be the most reasonable.

1. From a strictly historical point of view, the most interesting theory is that which finds the first suggestion of stalactites in what are apparently the earliest known Mohammedan buildings, the so-called tombs of Zobeide and of Ezekiel, near Bagdad, built by Haroun al Raschid about the year 810. These tombs are roofed over by successive ranges of overhanging brick niches, in ten or twelve stories, each niche being supported upon corbels, which in the tomb of Zobeide occupy the spandrels between the niches; in the tomb of Ezekiel, which seems to be a later development, they rest upon their summits. Both treatments are to be found in stalactite work. The interior of these tombs, if covered with a coat of stucco, would present very much the aspect of a stalactite dome. (Plate XI.)

2. One theory finds in stalactites an imitation in miniature of a form of domical construction still used in Persia. These domes are formed by a series of interlacing arches which leave between them diamond shaped panels, which in many examples are scooped out in the form of shells. The effect is not unlike some of the larger honeycomb domes of Egypt, one of which is illustrated in Plate XIII. But no historical connection between the two has been clearly made out.

For these suggestions I am indebted to a paper read before the Royal Institute of British Architects by my friend Mr. Spiers in April, 1888.

3. One might, however, if he were to disregard these intimations, fancy that the pile of niches, or small domes, which constitute the simplest and presumably the earliest variety of stalactite work, were an imitation, *in petto*, of the pile of great half-domes and niches to be found at the eastern end of the church of St. Sophia at Constantinople. (Plate XI.)

The imitation upon a small scale, for solely decorative purposes, of large constructive features, — such as columns, capitals and entablatures, arches and arcades, piers, brackets and

pediments, — is of frequent occurrence in all styles of architecture, and for a century before the Hegira these great niches and the spherical pendentives upon which they rest had been the wonder of the world as much for their grace and beauty as for their dignity and boldness. What more likely, then, than that they should be decoratively reproduced on a smaller scale? But in point of fact this seems not to have happened, even in the countries most directly under the influence of Byzantine art. It was not likely to happen in Egypt, for the Copts, in their art as well as in their religion, sedulously repelled all Greek influences, and the Byzantine dome with its pendentives played in fact little part in Mohammedan architecture until, a thousand years later, Constantinople was taken by the Turks. In Egypt, as afterwards in Persia and Hindostan, the transition from a square plan below to a circular dome above, or from a rectangular recess to the semicircular niche which covers it, is generally made by throwing arches across the corners, thus bringing the square to an octagon. The spandrels between the arches are not occupied by hollow spherical surfaces, as at St. Sophia, but are sometimes left plain, and sometimes filled with great polygonal or even star-shaped brackets. It is in this feature, not in the Byzantine half-domes, that we may perhaps find the prototypes of the little stalactite niches and of the corbels sometimes which support them. Examples of this are shown in Plate XI.

That from the Fayoum shows the inside of a dome of cut stone which passes from the square below to the circle above by way of eight-sided and sixteen-sided polygons. In the smaller one from the Tombs of the Caliphs, the arch thrown across the corner of the square is filled in with four rows of little niches which, with the broken spandrels between them, almost exactly reproduce in miniature the larger construction above. In this example the overhanging piers between the upper niches do not come in line with the piers below, the re-entering angle between the spandrels being ill-calculated to support them, but, as in the Tomb of Ezekiel, they rest upon the crowns of the niches, which are thrown forward to receive them.

In the larger one, however, of the niches form Cairo doorways, the spandrel is occupied with an octagonal, or even star-shaped, corbel, which also is reproduced in miniature between the niches of the stalactite work which fills the upper arch, to support the little piers that separate the niches. These may well have been suggested by the large ones below. The smaller niche also shows these star-shaped corbels.

It is to be noticed that these great corbels closely resemble the inverted polygonal and star-shaped pyramids which occur in some later developments of Gothic groining, though they lack the ribs which are the characteristic element in Gothic vaulting. The cusped and pointed arches, also, remind one of mediæval work. But this elaborate and beautiful development of Saracenic groining seems, curiously enough, to have been confined to these doorways, and not to have been used for the vaulting of interiors, which was probably considered too bold an undertaking.

The larger example from the Tombs of the Caliphs shows how rows of niches were made to take the shape and exactly fulfil the function of a Byzantine pendentive.

It was, moreover, a peculiarity of the Saracenic builders that, with a singular neglect of constructive propriety in design, they habitually left the arches which were thus thrown across the corners hanging in the air, without any supporting corbels at all, as may be seen in the example from the Fayoum. The constant recurrence of this curious treatment in the miniature stalactite niches, as is exemplified in the other domes, would seem to confirm the hypothesis that they owe their origin to the imitation of larger constructive members.

4. But it is hardly necessary to go so far afield as Persia or Bagdad, or even to suppose that stalactite work is the imitation in miniature of larger constructions nearer home, since the methods of brick building now used in Egypt offer forms closely analogous to them and of the same diminutive scale. The brick corbels habitually employed in modern construction look very much like the angular, or honeycomb, variety of stalactites, and they need only to be covered with a coat of plaster,

as walls in Egypt have always been covered, to produce what the Spaniards call the egg-shell variety, the plaster filling up and rounding off the sharpness of the angles. The four figures on the bottom of Plate XI illustrate this suggestion.

How much credence should be given to either of these hypotheses must depend upon the support afforded them by the facts of history, data which seem to be at present inaccessible. Without such support the most plausible and self-consistent theories are of little worth. But these inquiries are after all merely a matter of curiosity; for what gives vogue to manners and customs is the vital thing, not what starts them. The women now march off in a body at the end of a dinner, deserting the men, in order that each party may, for a change, consort for a while with their own kind, not, as in the origin of the custom, because the society of gentlemen in their cups is liable to become uncongenial to ladies. So here, and in the contemporary Gothic architecture, the important question is, not what first suggested stalactites and pointed arches, but why these varieties, or species, once planted, suddenly overran their respective fields, to the exclusion and suppression of other forms, with all the tyranny of a dominant fashion.

It is not so important to know what was the first hint of stalactites, as to know why the suggestion was taken up and developed with so much zeal. This seems to have been due to a predilection for geometrical ornament, and this, in turn, to have been due to the mystical turn of mind of the later Egyptians. A repugnance to the use of the human form, and even of the forms of animal and vegetable nature, was an eminently Coptic prepossession. The Mohammedan precept forbidding painting and sculpture is not found in the Koran, but the successors of Mahomet, in their exposition of the Koran, seem to have adopted the idea from the Copts, wishing probably to make converts among them. The Koran says one shall not *worship* the image of anything created, but the Copts went further and objected to making any representations of any created thing. This is now the teaching of the orthodox Mohammedans in nearly the entire Mohammedan world, although the

heretical Fatimites, both during their ascendancy in Cairo and nowadays in Persia, have largely rejected it.

The Copts were ascetics. It was in the Egyptian mountains that the solitary life of the first hermits was established. In their distrust of the natural world and its beguiling beauties they even went so far as to consider that curved lines were of the evil one. No right minded person would tolerate anything but right lines, and in their architecture the Coptic builders even revived the rectilinear arches which are found in the earliest Egyptian pyramids. In the decorative work of the Mohammedans, accordingly, the lines are nearly all straight and the few curved lines which are employed represent only geometrical figures. These predispositions had already been conspicuously manifested in the time of the Romans, who called the mosaics which were made up of square and triangular tesserae, carefully shaped and fitted, by the name of *Opus Alexandrinum*. Extraordinary skill and invention are shown also in the construction of interlacing patterns, and in the inlaying of marbles or other stones, often making the inlaid figure and the background of the same shape but reversed. The skill thus fostered found abundant exercise in developing all the possibilities of stalactite work, which by the time of its first appearance in existing buildings had attained an intricacy and complexity which well nigh baffles comprehension, and as we have seen, makes it almost impossible to tell in what structural suggestions it may have originated. In despair of finding any rational explanations, some writers have even turned to symbolism and fancied that the little niches of which the work is made up of are repetitions on a smaller scale of the Mihrab, or sacred niche, which in every mosque points the worshipper's face towards Mecca.

In view of all this we may not be far wrong if we take the view that, these accumulations of hollow niches having once commended themselves to the taste of the time, the same patient ingenuity and exuberant fancy which led to the elaboration of geometrical patterns in the flat, found in the problems of solid geometry which these studies presented, an equally congenial field. And just as in their patterns of wood and marble

inlays and interlacings, forms suggested by weaving and brick-laying, they adhered to the straight lines and circles which geometry affords, so here they enriched their cylinders, hemispheres, and parallelopipedons by adding to them whatever suggestions were offered by the groinings and corbellings of the stone-mason and brick-layer, thus giving a new interest to their work. One may as well suppose these to be the last steps in the process of development as the first.

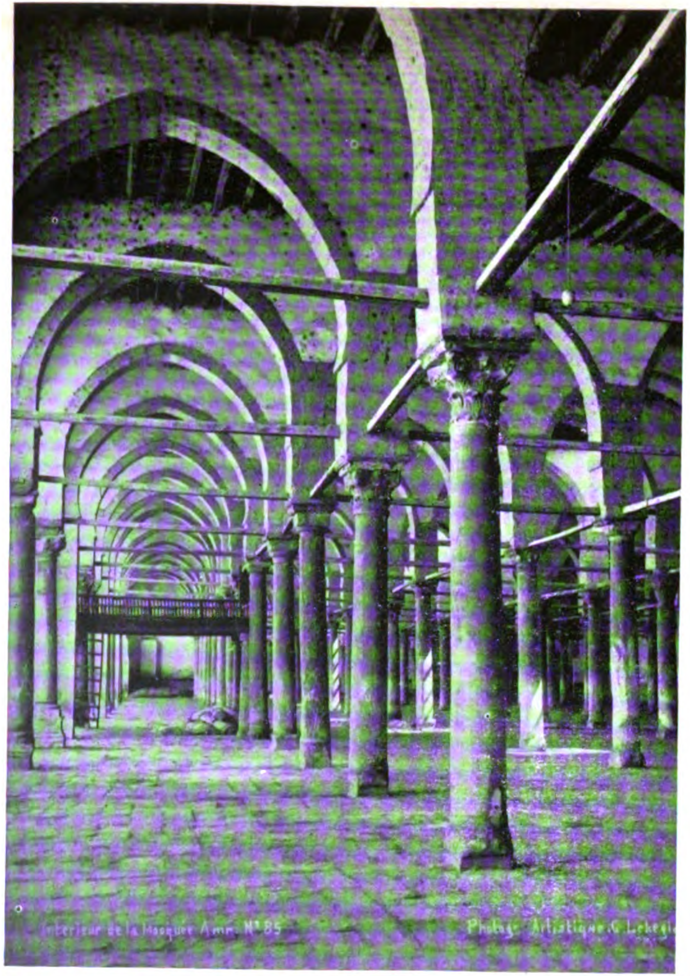
A less well-known example of their geometrical ingenuity is their solution of the problem of architecturally squaring the circle, so to speak; that is, of connecting a square figure with a circular one. This problem found its most famous solution in the pendentive dome of St. Sophia. The transition is there made by means of spherical triangles, and the Romanesque architects adopted the same device not only in their domes but, on a smaller scale, in making the transition from a round shaft to a square abacus or plinth, in the so-called "cushion" capitals and bases. But the geometrical Copts hit upon another device which was exceptionally clever and which better suited their rectilinear turn of mind. Knowing that between any three points a plane triangular surface may be drawn, they took any number of points on the circle and from these points passed zig-zag lines connecting them with an equal number of points upon the square. The surface connecting the square and the circle was thus divided into plane triangles, each of which was sometimes broken up into three smaller triangles by depressing a point in its centre; and these again sometimes given a similar treatment. Examples of this device are found in the base of the columns which flank the great doorway of the Mosque of Sultan Hassan, and in the base of the minarets of the mosque at Boulak and of the Suleimanieh at Constantinople. Several capitals in Cairo and those in the porch of the Mosque of Rustem Pasha, also in Constantinople, exemplify the same method. My friend Mr. Partridge has furnished me with a curious example of the same thing from the church of St. Remi at Rheims. (Plate XII).

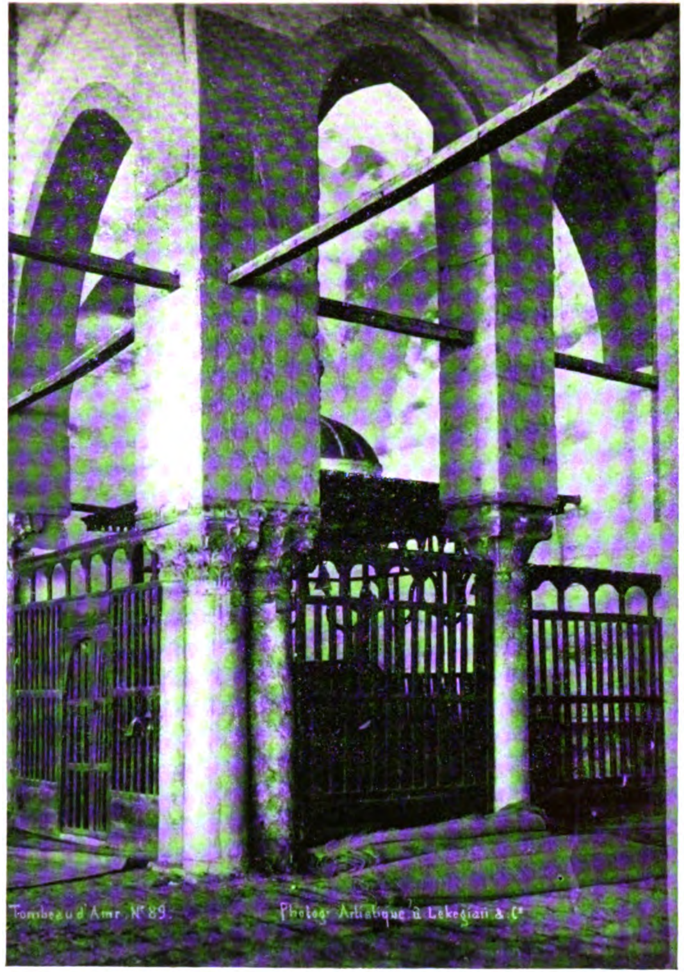
The same device is employed on the outside of the Tombs of

the Caliphs and of the Mamelukes at Cairo, to pass from the square walls below to the base of the circular or polygonal dome above. An elaborate series of large mouldings, like a gigantic chamfer-stop, was also adopted in these buildings to give to the exterior surface of the pendentives an appropriate architectural treatment, a problem which both the Gothic and the Renaissance architects have constantly evaded. (Plate XII.)

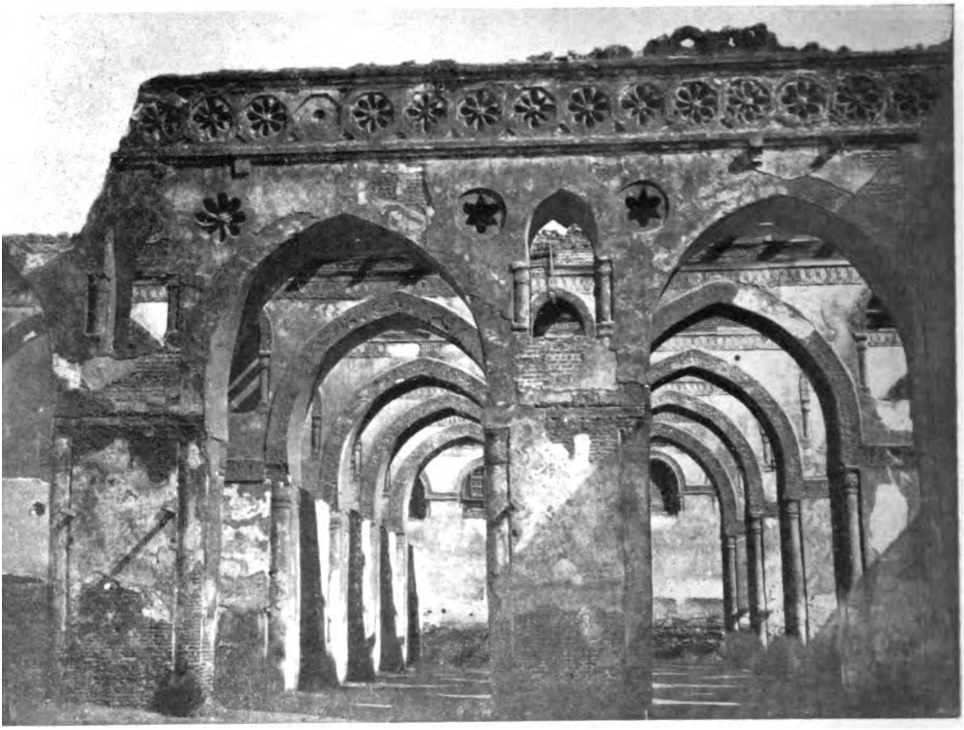
The most interesting application of this expedient is to be found, however, not in Constantinople or in Cairo, but at Broussa, where the Ottoman Turks established themselves, as has been said, before crossing into Europe. In the domes of several of the mosques, and in a great niche, a half-dome, at the entrance to one of them, the transition from the square below to the circle above is effected in this manner. (Plate XII.) One of the examples shows each of the original triangles occupied by nine smaller ones. I do not know that these buildings have yet been published, or that attention has been called to these clever geometrical constructions.

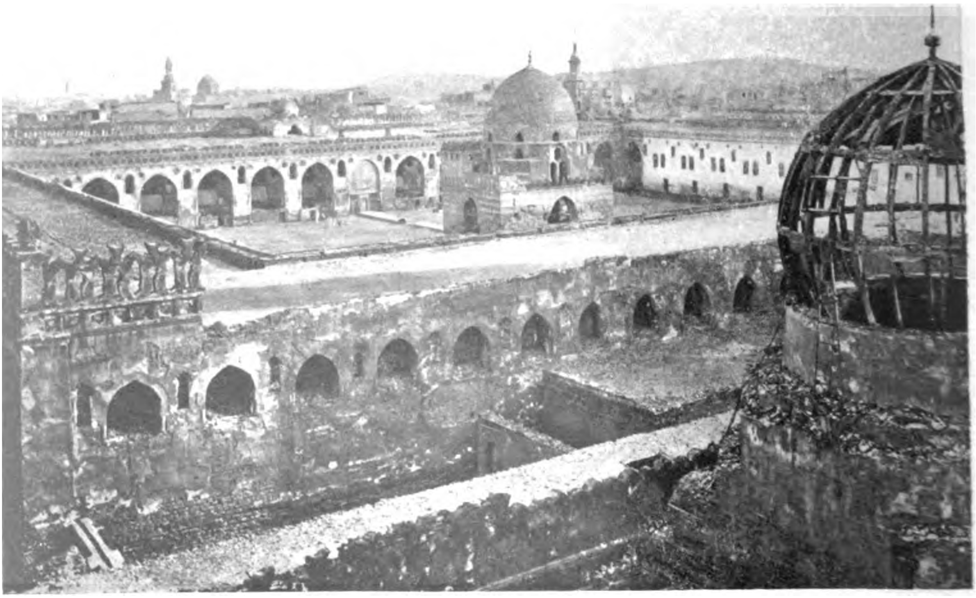
Other distinctive devices of the Mohammedans are the horseshoe arch and dome, and the domes supported upon intersecting arches which are to be found in Sicily, Spain, India, and Persia. But any discussion of these, or of the more purely decorative methods of the Mohammedans, would take more space and time than are now at our command.





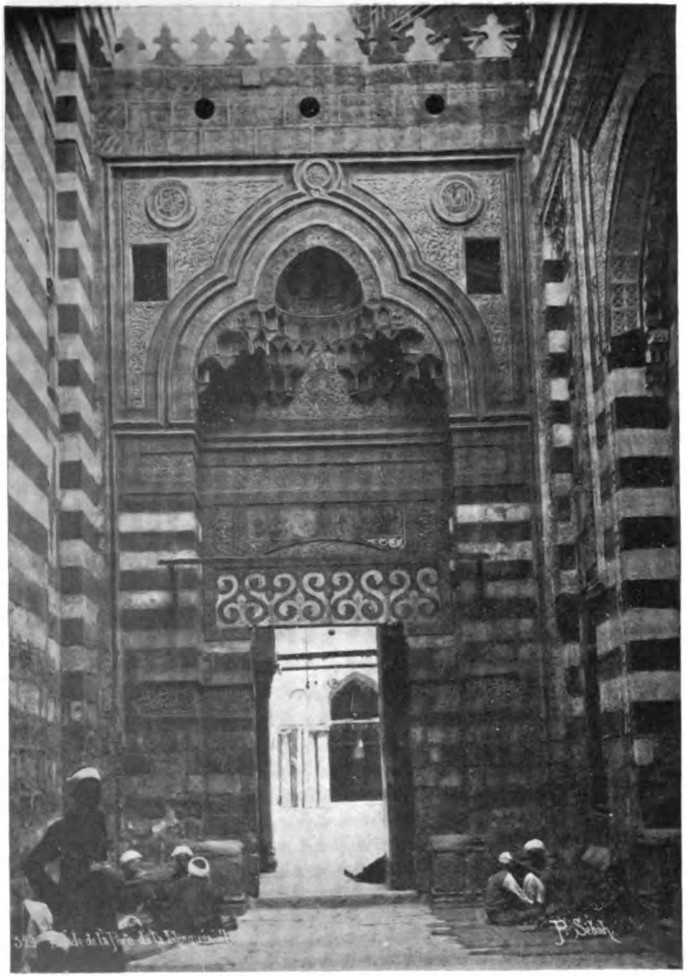
THE MOSQUE OF AMROU, A.D., 642.





THE MOSQUE OF TOULUN, A. D. 876.

PLATE IV.



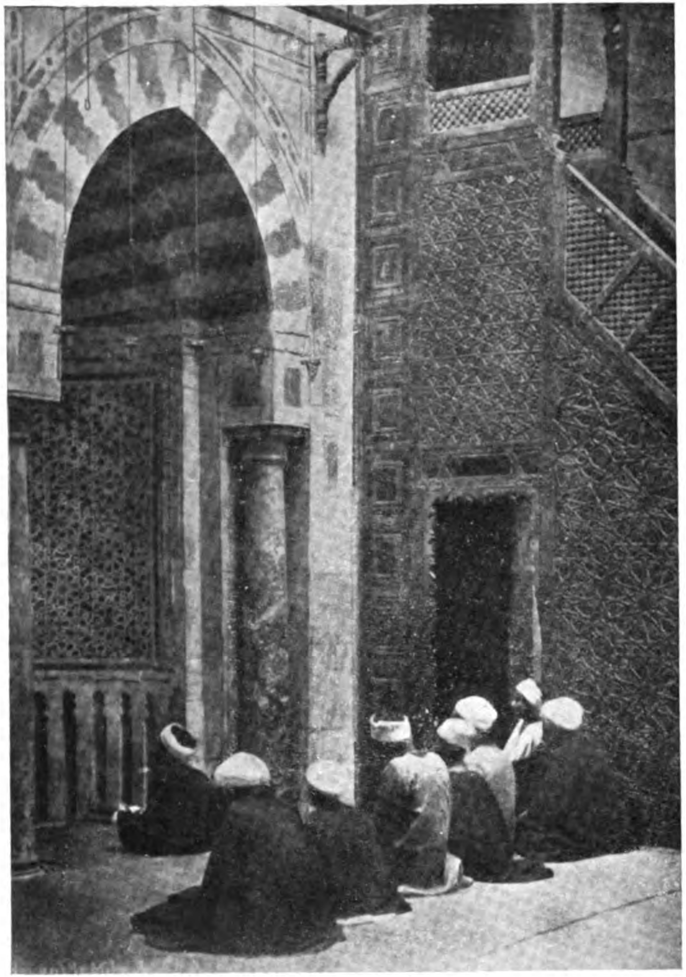
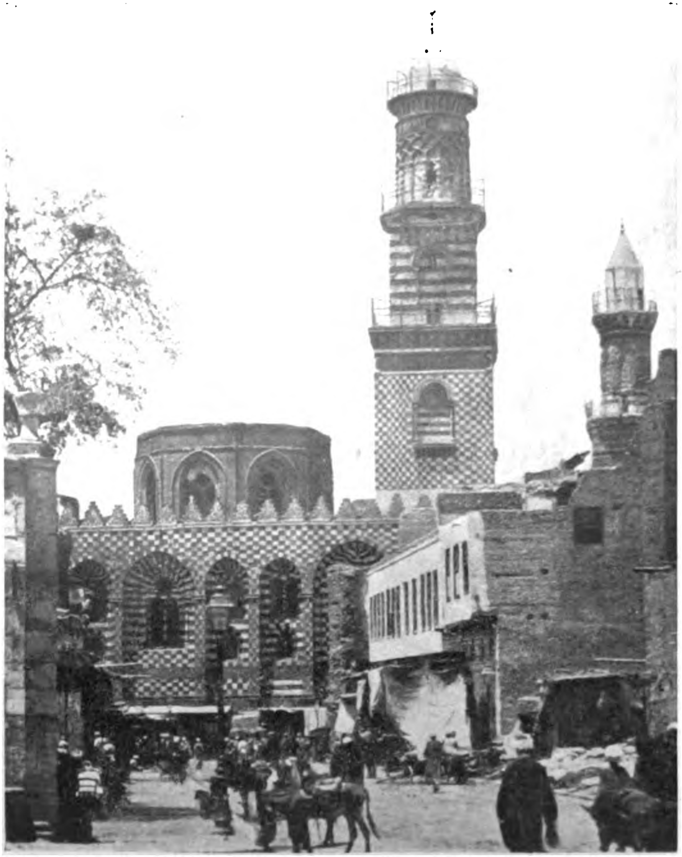
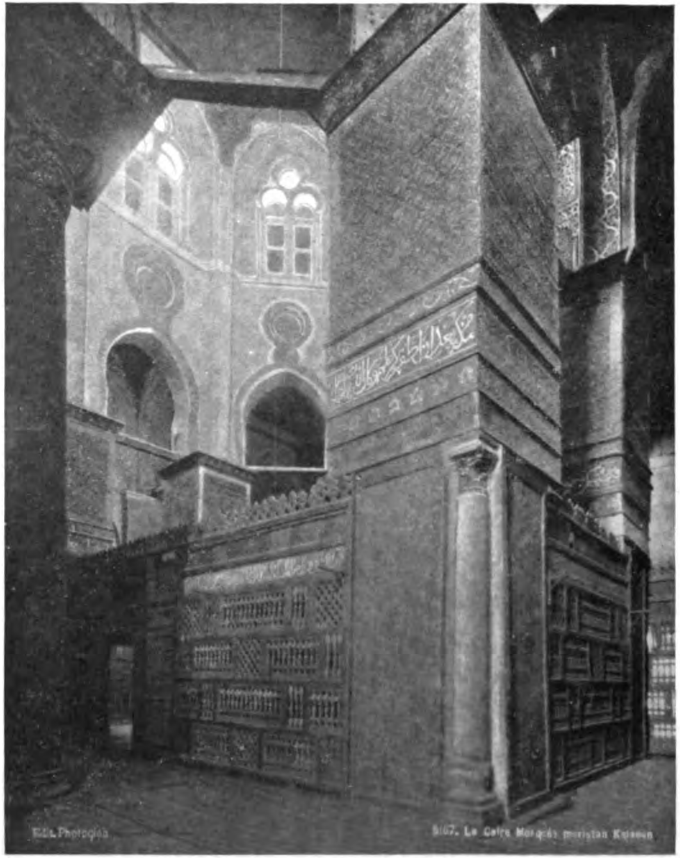


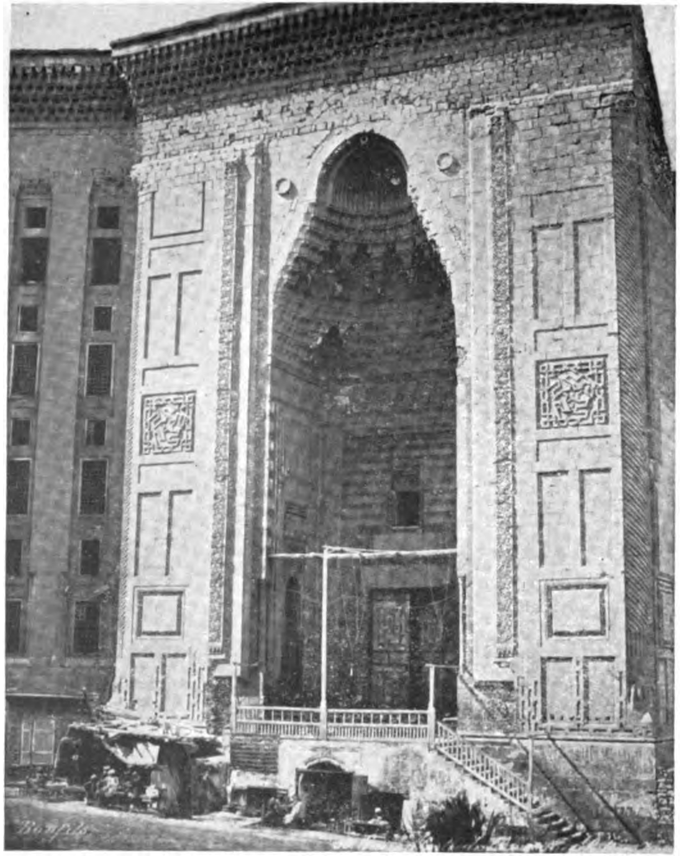
PLATE V.

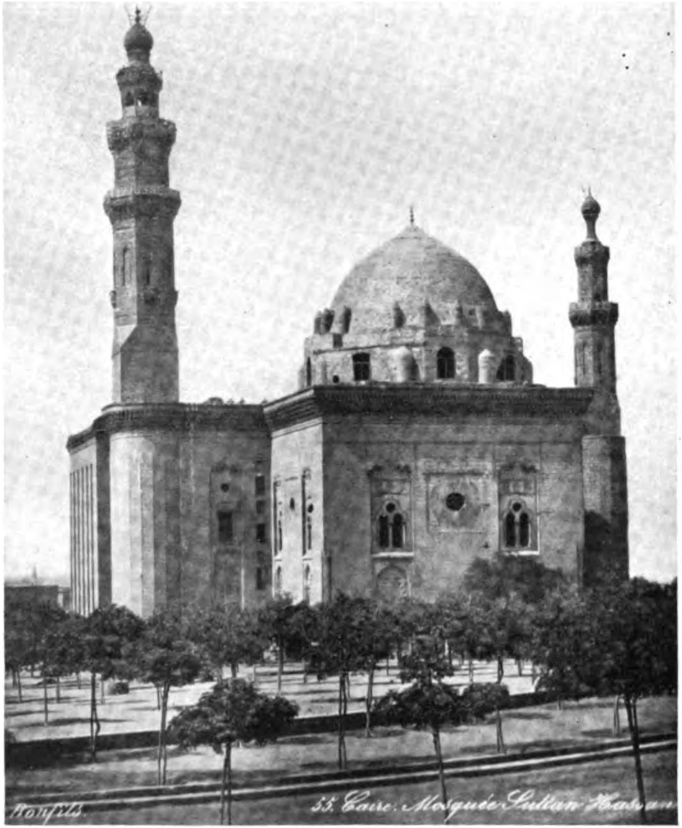




THE MOSQUE OF SULTAN KALAHOUN, A. D., 1287.

PLATE VI.

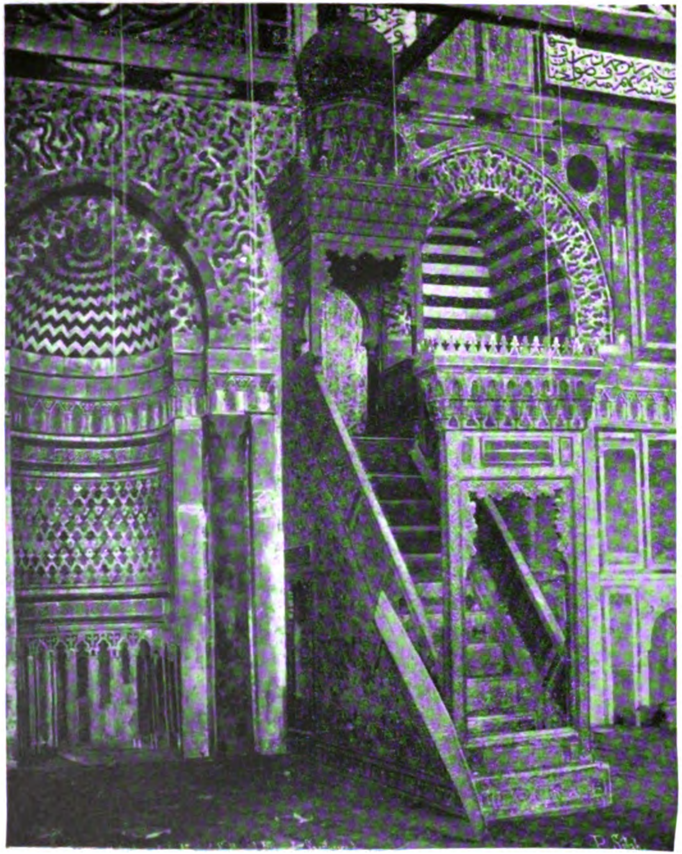


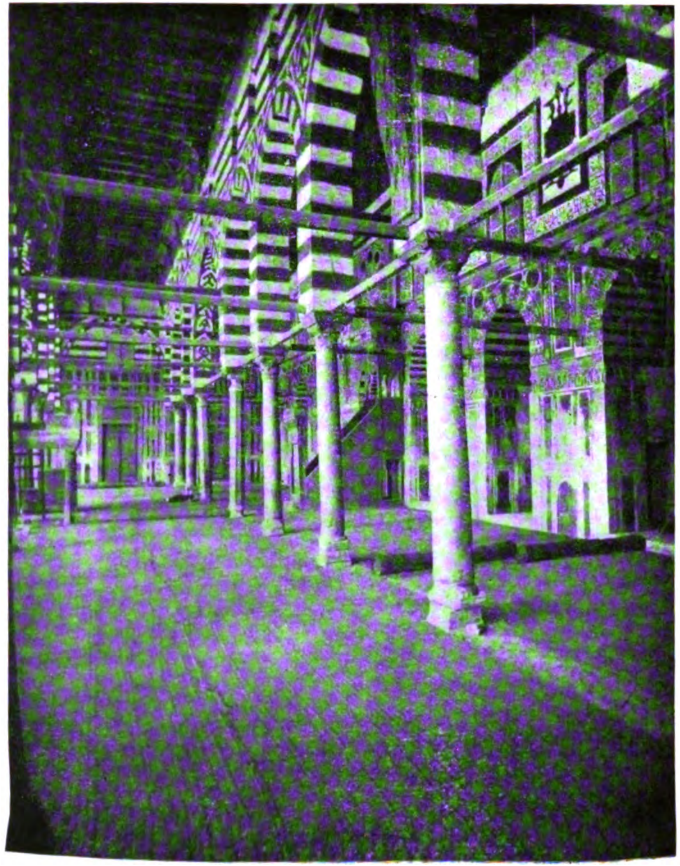


THE MOSQUE SULTAN HASSAN, A. D., 1377.

PLATE VII.

THE MOSQUE OF BARQUOQ. A. D., 1382.



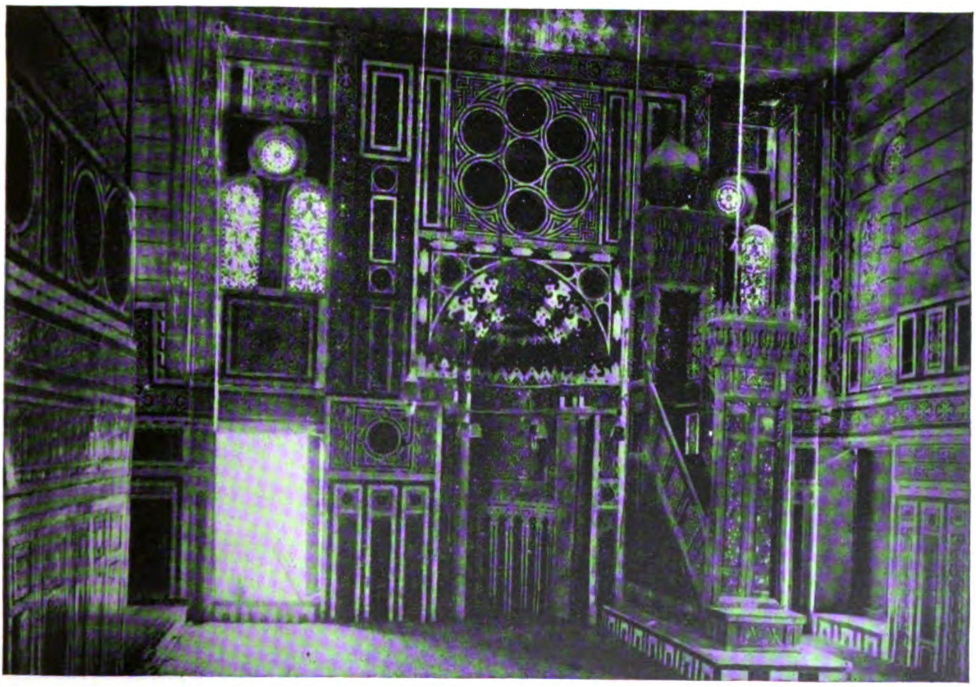


THE MOSQUE OF MOAYED, A. D., 1412.

THE CITADEL OF SALADIN, A. D., 1166.
THE MOSQUE OF MEHEMET ALI, A. D., 1815.

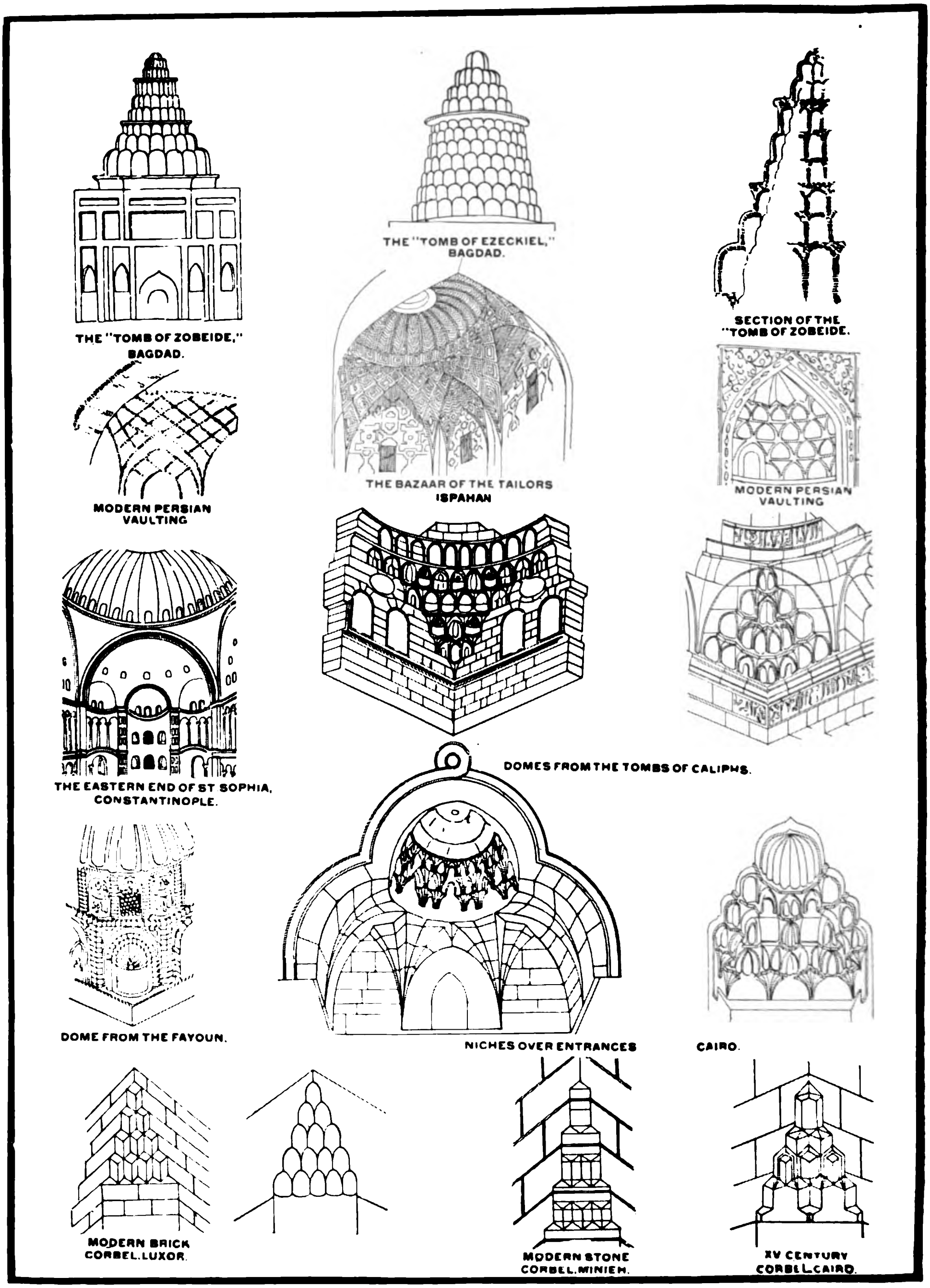
THE MOSQUE OF KAIT-BEY, A. D., 1463.

THE MOSQUE OF BOULAK, A. D., 1571.

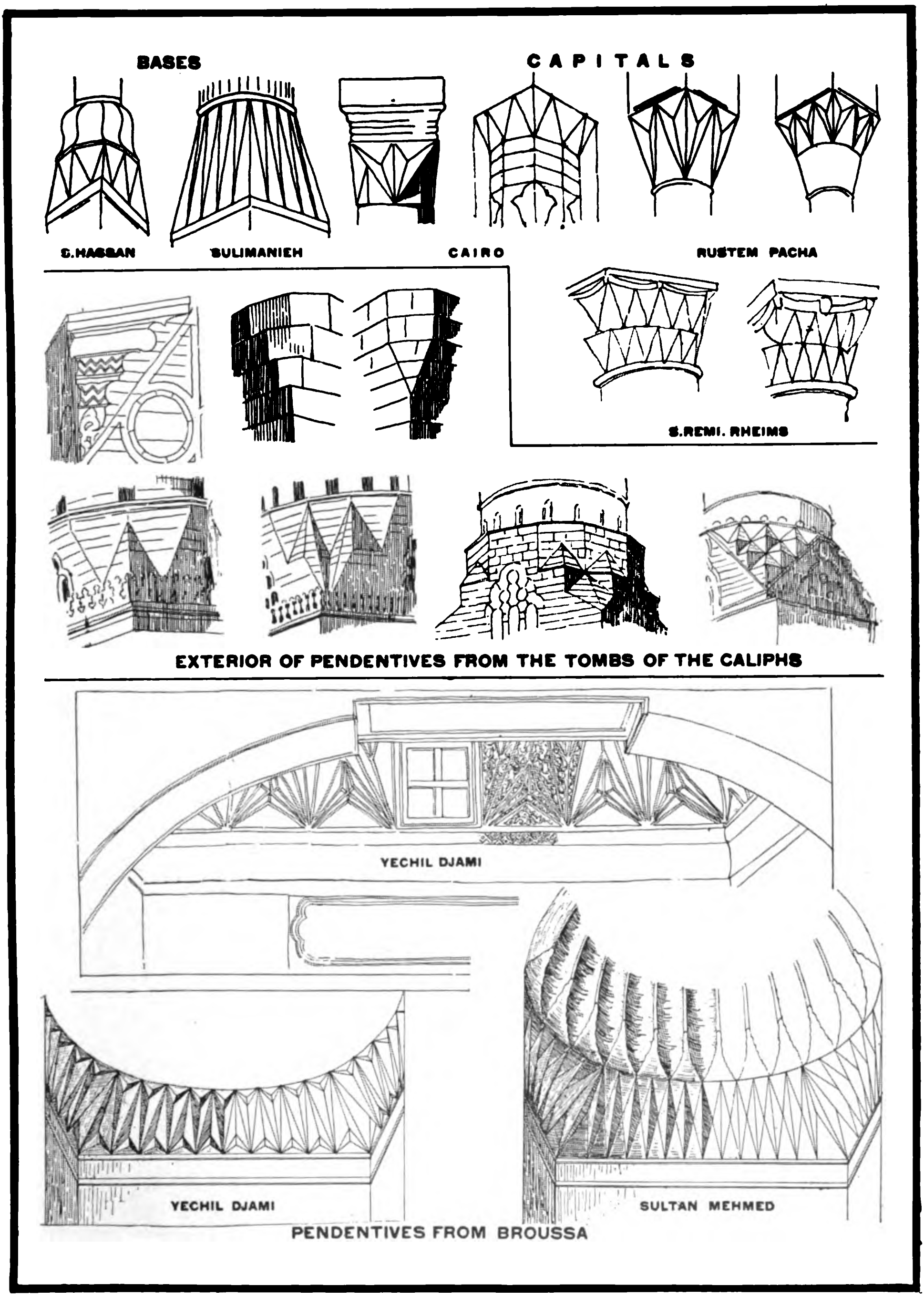


THE BORDENI MOSQUE, A. D., 1638.

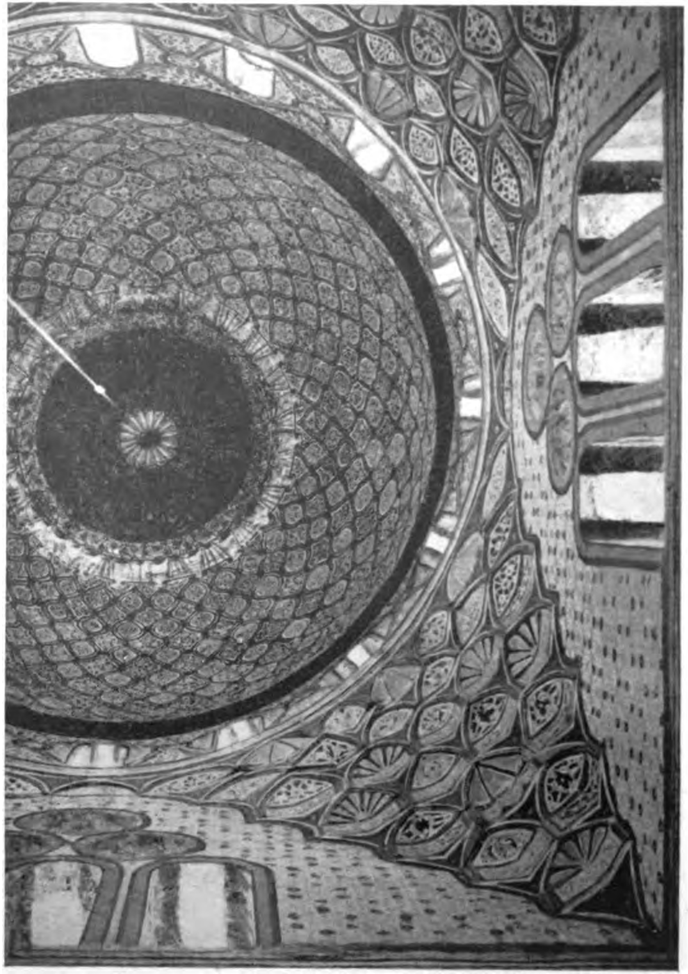
PLATE XI.



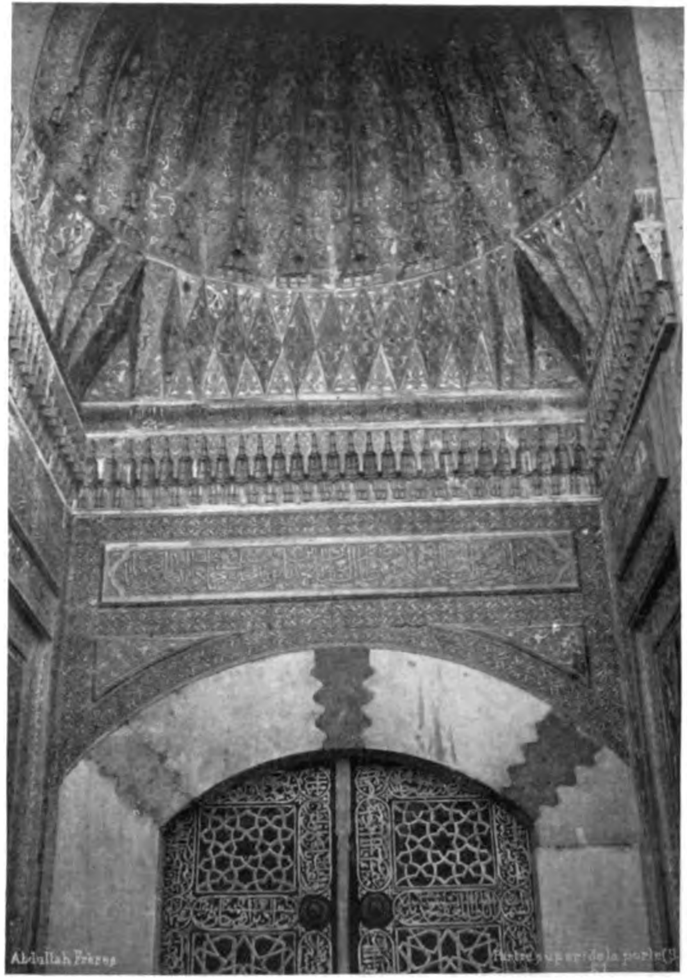
STALACTITES.


BASES
CAPITALS
S. HASSAN
SULIMANIEH
CAIRO
RUSTEM PACHA
S. REMI. RHEIMS
EXTERIOR OF PENDENTIVES FROM THE TOMBS OF THE CALIPHS
YECHIL DJAMI
YECHIL DJAMI
SULTAN MEHMED
PENDENTIVES FROM BROUSSA

ZIGZAGS.



DOME OF THE MOSQUE OF MOHAMMED BEY, CAIRO, A. D., 1774.



DOORWAY OF THE MOSQUE OF SULTAN MEHMED, BROUSSA, A. D., 1389.

SOME NEW DATA ON THE WEIGHT OF A CROWD OF PEOPLE.*

By Lewis J. Johnson, Assistant Professor of Civil Engineering, Harvard University.

[Read before the Harvard Engineering Society, January 12, 1904.]

The weight of a crowd of people is one of the most important bits of data used by the structural engineer. It would seem to be one of the most easily determined, yet it is one on which the authorities differ widely, and one which they understate and, with few and unfamiliar exceptions, seriously understate. The engineering practice of both Europe and America accords closely with Trautwine's recommendation: †

"On bridges for turnpikes and common roads, no probable contingency could crowd people to such an extent as to weigh more than 80 lbs. per sq. ft. of floor; and this may safely be taken as the maximum load on spans of 20 or more feet. To compensate, however, for impact, we recommend to adopt 100 lbs. as the limit for crowds."

In a footnote on the same page, Mr. Trautwine cites experiments in support of the preceding, as follows:

"The engineers of the Chelsea bridge, London, *packed picked* men upon the platform of a weigh-bridge; with a result of 84 lbs. per sq. ft. Mr. Nash, architect of Buckingham Palace, *wedged* men together as closely as they could possibly stand upon an area of 20 ft. diameter; the last man being lowered down from above, among the others. Result, 120 lbs. per sq. ft."

While 80 to 100 lbs. per sq. ft. are generally accepted as the maximum for bridge-work, the city building laws of this country

* Read before the Boston Society of Civil Engineers, December 21, 1904. Printed through the courtesy of the *Journal of the Association of Engineering Societies*.

† *Civil Engineer's Pocket Book*, 18th edition, p. 726.

specify 80 to 150 lbs. for the minimum floor loads for public assembly rooms — some cities naming the lower value, others the higher, and others still giving various intermediate values.

Why the proper assumptions for buildings have been commonly held at a higher figure than for bridges, it is not easy to say. Perhaps it is because the increased cost of the building by leaving a larger margin is relatively a less serious matter than with a bridge, and the incentive for close figuring relatively less felt. An additional factor may be that the likelihood for defective construction may have been regarded somewhat greater in the cases of buildings than with bridges. It certainly does not seem attributable to any current belief that the weight of crowds might reach 150 lbs. per sq. ft., for such a belief would certainly have been felt in bridge practice.

However this may be, the writer has been slowly coming to distrust the correctness of prevailing ideas on the whole subject, and for some months past has been making experiments in the attempt to get some first-hand information. The men at his disposal were his own students, and their patient and intelligent interest have alone made the work possible. The results up to last April were duly published * and accompanying them a series of nine extracts from writers of various countries. The writer had at that time obtained a maximum result of 156.9 lbs. per sq. ft., due to 67 men, averaging 151.5 lbs. each, in a space of 64 sq. ft. The authorities quoted in the nine extracts gave some 80, some 120 lbs. per sq. ft. as the maximum possible from a stationary crowd, one only going above 120. Mr. Stoney reported 147.4 lbs. per sq. ft. from 58 Irish laborers, averaging 145 lbs. each, packed into a space of 57 sq. ft. It was observed that the authorities, with the exception of Stoney, rarely cited any deliberately conducted experiment. The best known experiments are those quoted by Trautwine and given above. Stoney's seem to have been generally overlooked.

The result published last April was roughly verified † by Professor Spofford, of the Massachusetts Institute of Technology,

* *Engineering News*, April 14, 1904, p. 360.
† *Engineering News*, May 5, 1904, p. 426.

and later by a German investigator in Bonn.* These gentlemen reached results of 142.5 and 144 lbs. per sq. ft., respectively, each making it clear that the limit had not been reached. In the discussion that followed, the results of Professor Kernot, of Melbourne, were recalled. He reported † 143.1 lbs. per sq. ft. as his maximum.

The writer gave the matter no further attention till within the last few weeks, when two of the foremost American structural engineers publicly expressed their belief that a load from a crowd of people in buildings in excess of 40 to 45 lbs. per sq. ft. is not exceeded in practice often enough to demand much consideration.

One of these gentlemen, Mr. C. C. Schneider, stated ‡

"A live load of 40 lbs. per sq. ft. . . . . may be considered the maximum load to be provided for as a distributed load for all floors on which crowds of people may be expected to congregate."

To allow for vibrations in the case of ballrooms, drill rooms, gymnasiums,§ etc., he recommended assuming an additional 40 lbs. per sq. ft., after stating that

"a uniform load of 40 lbs. per sq. ft. will scarcely ever be exceeded by a crowd of people."

Mr. Theodore Cooper,‖ in supporting Mr. Schneider's assumption of 40 lbs. per sq. ft. and in illustrating the rarity of a load above that figure, says:

"Most people have experienced the discomforts of a crowded Elevated Railway car when not another person can be squeezed inside of the gates. Such a crowd, numbering about 120 persons and not weighing more than 18,000 lbs., is contained in a space of about 400 sq. ft., including platforms, or 45 lbs. per sq. ft."

* *Zentralblatt der Bauverwaltung*, October 8, 1904, and *Engineering News*, November 3, 1904, p. 406.

† *Engineering News*, March 16, 1893, p. 252.

‡ *Proceedings American Society of Civil Engineers*, Vol. XXX, p. 676.

§ Ibid., p. 680.

‖ *Proceedings American Society of Civil Engineers*, November, 1904, p. 851.

FIG. 1.—41.8 LBS. PER SQ. FT.
10 men averaging 150.6 lbs. on 36 sq. ft.)

FIG. 2.—SAME MEN AS IN FIG. 1, DIFFERENTLY SPACED.

FIG. 3.—41.8 LBS. PER SQ. FT.
(5 men, averaging 133.8 lbs., on 16 sq. ft.)

FIG. 4.—47.2 LBS. PER SQ. FT.
(11 men, averaging 154.6 lbs. on 36 sq. ft.)

FIGS. 1–4.—CROWDS WEIGHING 41.8 AND 47.2 LBS. PER SQ. FT.

In view of these statements, the time seemed appropriate for further work on the problem, and for the sake of taking part in the discussion with Messrs. Schneider and Cooper, the writer had a series of photographs taken showing bird's-eye views of crowds at different degrees of compactness from 40 to 150 lbs. per sq. ft. These photographs are reproduced in Figs. 1 to 8, and are sufficiently explained by their titles. Special attention may be called to Figs. 1, 2, and 3 as representing crowds approximating Mr. Schneider's 40 lbs. per sq. ft. and to Fig. 4 as showing a crowd somewhat *more* compact than Mr. Cooper's Elevated Railway crowd.

In Fig. 3 the men are in an alcove four feet square. Specially light men were selected for this test for the sake of showing a specially crowded example of 40 lbs. per sq. ft. One less man, if the average were 160 lbs. each, would produce the requisite 40 lbs. with considerably less appearance of crowding.

In Fig. 7, the very high average weight (167.7 lbs. per man) is due to the fact that the crowd shown is the remnant of the crowd of Fig. 9 after twelve of the lighter men near the gate had left the box.

In all the experiments in close crowding, the men were, up to this time, left to arrange themselves.* They naturally stood entirely at random, facing in all directions.

Obviously, the next step was to see what could be reached by facing the men all one way, especially as they would be likely to be so arranged in a constriction in a street caused by a drawbridge or in standing in a crowded meeting. At the same time some care was taken to select tall men, with a view to finding out what a crowd actually might weigh. The result, to the writer's great astonishment, was on the first trial of this process 176.4 lbs. per sq. ft., due to 40 men in a space 6 ft. square. A repetition of it was made for the sake of a better photograph and somewhat better selection of men. The result (Fig. 9) was 181.3 lbs. per sq. ft., due to 40 men, averaging 163.2 lbs. each, in a space of 6 ft. square. This result is, of

* Except in Fig. 7, which, as just stated, was taken after Fig. 9.

Fig. 5.— 83.7 Lbs. per Sq. Ft.
(20 men, averaging 150.7 lbs.)

Fig. 6.— 100 Lbs. per Sq. Ft.
(24 men averaging 150 lbs.)

Fig. 7.— 130.4 Lbs. per. Sq. Ft.
(28 men, averaging 167.7 lbs.)

Fig. 8.— 154.2 Lbs. per Sq. Ft.
(37 men, averaging 150.1 lbs.)

Figs. 4–8.— Crowds Weighing Between 80 and 155 Lbs. per Sq. Ft., Occupying in Each Case a Space of 36 Sq. Ft.

course, an extreme, evidently to be put in the same class with the 84 lbs. and 120 lbs. in the quotation from Trautwine.

Though 181 lbs. per sq. ft. must be conceded to be an extreme, it is believed that something very close to that figure is reached over the whole drawbridge on the way from Soldier's Field to Harvard Square after one of the great football games.

Moreover, if 40 men, averaging 163 lbs. each, can stand in no serious discomfort in 36 sq. ft., it is clear that 40 men of the ordinary size of 150 lbs. each could easily do so. The result then would be 166.7 lbs. per sq. ft.

The great increase in the results of this fall over those of last spring seems to be due largely to the better economy of room from facing the men all one way and partly to the dimensions of the box being such as to work up with little waste room, both of which are conditions favoring congestion to be met in practice.

The conclusion seems irresistible that loads of 180 lbs. per sq. ft. may actually occur in exceptional cases; that 160 lbs. must frequently occur; that 140 lbs. must be common on station platforms, in corridors and many other places frequented by throngs of people; that 80 lbs. per sq ft. must be common at social gatherings in private houses. The conclusion is equally clear that the margin of safety in many existing structures designed for 80 to 100 lbs. per sq. ft. (to say nothing of 40 to 45) must be much less than has been supposed. Probably the correct inference is that the experience of many years in many lands has demonstrated that the margin has been sufficient, nevertheless. Even if that be true, it is no reason why we should remain in the dark about how much a crowd of people actually does weigh. It is only with the correct knowledge of the maximum that engineers can intelligently decide for what load any part of any structure may properly be proportioned. In thus deciding, it will not be forgotten that a crowd of people is the very last load which should be endangered by too small a margin of safety even "once in a great while."

Fig. 10 shows the box or pen in which the men gathered (after being weighed inside the building) and the scaffolding

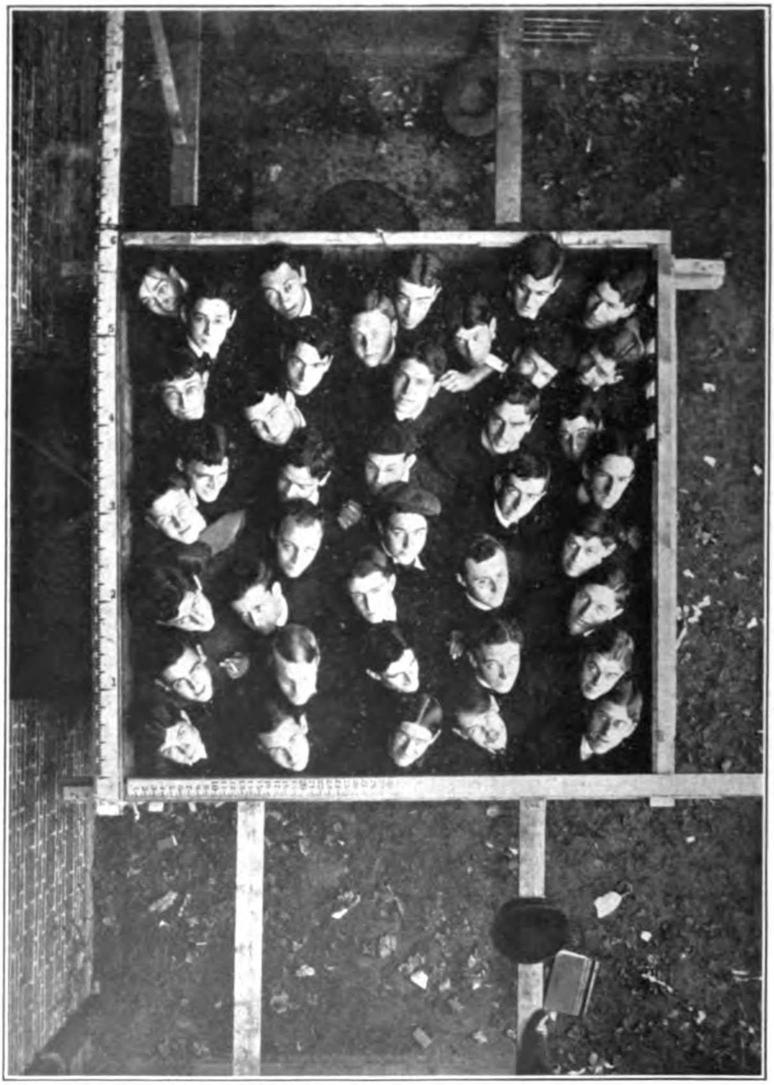


FIG. 9.— 181.3 LBS. PER SQ. FT.
(40 men, at 163.2 lbs. average, on 36 sq. ft.)

on which the camera was mounted. The lens was pointed directly downward. The men entered the box through the gate at the right, and when the box was full the gate was closed and secured by the heavy bar shown. The braces running to

FIG. 10.—APPARATUS USED IN PHOTOGRAPHING CROWDS FOR THE DETERMINATION OF FLOOR LOADS.

the side of the porch and the wall of the building were for strengthening the box against internal pressure, which, with forty men in the inclosure, became considerable — especially

when they took it into their heads to take a long breath simultaneously. The men were requested to look up toward the camera so as to be more easily distinguishable for counting, and so as to be identifiable as a check upon the records.

It may be interesting to add that what may be called the asymptotic value of the weight of a crowd of men must be about 218 lbs. per sq. ft. (possibly more than this rather than less with men of varying height). This figure was reached upon examination of data kindly furnished by Dr. Sargent, Director of the Harvard Gymnasium. It was obtained by dividing the weight of a man 6 ft. 3 in. tall, a former football captain, by his maximum horizontal cross-section as obtained by a planimeter. This maximum section was, of course, through the chest, including the arms. The weight of this man was 177 lbs., and maximum cross-section 117 sq. in., both quantities exclusive of clothing.

In closing, the writer takes pleasure in thanking not only the students who cheerfully submitted to the packing process, but also many colleagues and friends, particularly Professor W. S. Burke, for their general assistance, and Mr. E. E. Pettee, Assoc. M. Am. Soc. C. E., and Mr. N. E. Olds, for taking the photographs.

TRAIN RESISTANCE.

By C. O. Mailloux.

(Continued from the January, 1905, issue.)

If, as our preceding reasoning would indicate, the tractive effort per wheel, as due to an "unclean track," decreases and tends toward zero for the rear wheels of a train, it follows that the train resistance, as usually measured, in pounds per ton, is influenced, in some inverse ratio, by the *number of wheels* in the train. Consequently we should expect that portion of the train resistance which is due to an unclean track to be lowest of all in the case of very long trains and highest of all in the case of single cars, and to be even greater for a four-wheel car than for an eight wheel car. There is reason to believe that the relatively high values found for train resistance (in lbs. per ton), on street railways can be accounted for to a great extent, if not wholly, on that hypothesis.

The total tractive effort (F_t) for a whole car or train is, of course, equal to the sum of the individual tractive efforts (F_1, F_2, F_3, etc.), for each of the wheels, thus:

$$F_t = F_1 + F_2 + F_3 + \text{etc.}$$
$$= W_1 \sin a_1 + W_2 \sin a_2 + W_3 \sin a_3 + \text{etc.},$$

where each term corresponds to a value consistent with equation (2a), $F = \frac{x}{r} W = W \sin a$, W being taken in pounds, when the values of F are wanted in lbs.

Dividing the total value (F_t) by the total *tons* of train weight, we have the corresponding *train resistance*, in pounds per ton, thus:

$$\frac{F_t}{1/2000(W_1 + W_2 + W_3 + \text{etc.})} = F_r = \text{lbs. per ton.}$$

When the weight per wheel is approximately the same for all the wheels, the same result can be obtained in a simpler way, for,

taking W = 1 ton = 2000 lbs. in (2a), the individual values, F', F'', F''',)etc., will now be in pounds per ton, and the train resistance, in pounds per ton, will therefore be equal to the arithmetical *mean* of these values, or

$$F_r = \frac{1}{N} (F' + F'' + F''' + \text{etc.})$$

where N = the total number of wheels of the train or car.

We can appreciate the importance of a clean, smooth track, if we calculate the tractive force (F), required to make a car wheel climb over "intermittent" obstructions of different sizes, for we

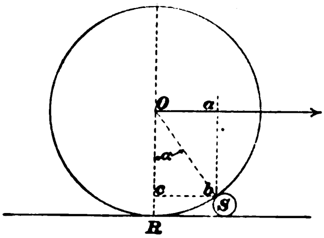


FIG. 12.

find that a very small elevation above the rail level gives a surprisingly high value for F. Using equation (3),

$$F = \frac{\sqrt{z\,(2r - z)}}{r - z}\,W$$

which is especially convenient for this purpose, (since z = the height Rc in Fig. 12), and taking W = 2000 lbs. = 1 short ton, we find, in the case of a 33 inch wheel (where r = 16.5), the following results:

HEIGHT OF OBSTRUCTION (z)	TRACTIVE FORCE PER WHEEL (F)	EFFECTIVE FICTITIOUS GRADE	
		Angle ($\beta_r = \alpha$)	Per cent
0.0005 inch	15.57 lbs. per ton	0°26′46″	0.78
.0010 "	22.02 " " "	0°37′51″	1.10
.0050 "	49.25 " " "	1°24′38″	2.46
.0100 "	69 66 " " "	1°59′42″	3.48
.0500 "	156.06 " " "	4°27′42″	7.80
.1000 "	221.20 " " "	6°18′41″	11.06

The figures in the second column represent maximum values of F, attained at the time when the whole weight has become transferred to the obstruction, the "fictitious grade" then being as indicated in the last two columns. The mean value (F_m) of the tractive force per wheel, depends greatly upon the number and disposition of the obstructions. When they are relatively few in number, the mean value, F_m, may be very small as compared with the maximum value. When they are very numerous and so disposed as to make a practically continuous obstruction, the mean value will be approximately the same as that maximum instantaneous value which corresponds to the mean value of the fictitious grade. Between these two extremes the mean values of F may vary greatly. The mean value for the *train* (which is obtained in the manner already explained) is itself susceptible of considerable variation.

The increase in train resistance due to sand on the track has not been definitely determined. On steam roads it does not appear, however, to represent a very great increase in total tractive effort, probably because the "fictitious grade" has almost, if not entirely vanished by the time the locomotive and tender (which exert the greatest pressure densities) have passed over the sanded track. The additional tractive effort required. on account of the sand, may possibly be, therefore, *approximately constant, per train*; hence, when it is apportioned over the whole train weight (which is usually considerable) the resulting value, in pounds per ton, is likely to be small, probably seldom if ever exceeding 5 lbs. per ton. On street railroads, on the other hand, the effect of sand is generally considered to be much greater, the increase in train resistance on account of it being variously estimated at values ranging from 5 lbs. to 25 lbs. per ton.

The effects of dust, dirt and mud are practically negligible on all roads which have a private right of way, as is the general rule with steam roads, and as is also the case with many interurban electric roads. In the first place, the "*tee*" rail, used on all such roads, does not easily retain these substances. In the second place, it is only at grade crossings that there is oppor-

tunity for their being deposited on the track by ordinary wheeled vehicles. On most street railroads, however, the case is entirely different. The top of the rail is usually below the level of the pavement, the result being, generally, as if the rail head formed the bottom of a depression (usually shallow, but sometimes quite deep), which forms a receptacle, and which generally accumulates a good share of about everything that is "loose" on the street, including sand, dust, dirt, grit, mud, refuse, etc. The depositing of these substances over the rail head is done in various ways, but mostly by horses and wheeled vehicles, especially the wheels of the latter, which, most of the time, roll in or near the grooves wherein the rails are placed, and act effectively as conveyors and distributors. The "obstruction" due to this deposit differs but little in nature and probably only little in degree also, in most cases, from that due to sand. It is generally regarded by engineers as the principal cause of the relatively great discrepancy in the train resistance values (lbs. per ton) found on steam railroads and on electric street railroads. The equivalent fictitious grade is supposed to vary, under different conditions, from 0.1 % to 1. % or or even more, representing (for a ton of 2000 lbs.) train resistance values ranging from 2 lbs. to 20 lbs. (or more) per ton.

The rolling friction caused by snow is not usually serious on steam roads, though it is not negligible in some cases.

The elevation of the rail above the ties and ballast usually allows sufficient room for the snow to be readily dislodged or pushed away sidewise, from under the wheel treads. In the case of deep and drifting snows, however, the rail is often covered again by the snow immediately after each wheel has passed. In such cases, although the snow yields readily under the pressure of each wheel, and therefore the fictitious grade is very low, yet, being present at each wheel of the train, and its "percentage" being practically the same for the whole train, it may sometimes cause an appreciable increase in the train resistance per ton. On street railroads the fictitious grade caused by snow is always appreciable, and in some cases, it may be relatively high, this result being due primarily to the peculiarity of

construction of the track which we have justed noted. The depression in which the rail is placed facilitates the accumulation of the snow and the formation of a deeper and more compact layer over the rail head than would be possible in the case of ordinary tee-rail track construction. The process of dislodging the snow from under the wheel is more complicated and requires more pressure because the sides of the depression obstruct the snow which is squeezed off the rail head. Finally the admixture of dirt and mud, containing grit, with the snow that has to be thus squeezed off, further increases the resistance of the "obstruction." There is reason to believe that the train resistance due to snow on city street railroad tracks may amount to as much as 10 lbs. per ton, corresponding to a fictitious grade of 0.5 %. In the absence of more definite data, it may be assumed, provisionally, that the fictitious grade due to snow on the rails may range from 0.05 % to 0.5 %. The rolling friction due to ice and sleet may be considered as particular cases of that due to snow. There are no definite data available regarding the influence of this kind of rolling friction on train resistance. In all cases where the presence of ice or sleet renders the track too "slippery," *i. e.*, when the rail-friction is too much reduced, the necessity of using sand to increase the "adhesion" necessarily occasions a material increase in the train resistance. On city street railroads the ice formed from the muddy water covering the rail will contain grit, which, while preventing slip will also materially increase the train resistance.

The rolling friction due to non-yielding inequalities of surface is exemplified in the case of open or imperfect rail joints, also the "gap" at switch frogs, and the high or low spots on the rails. These are all "obstructions" of the "intermittent" kind, constituting, indeed, the best illustrations of that particular kind. In the case of an open rail-joint, the wheel first *falls* into the gap between the rail ends, and it is then lifted up bodily out of it, the lifting process being substantially identical with that involved in passing over an obstructing particle such as typified in Fig. 12. In the case of a high spot on the rail or a high end at a joint, the process may be reversed,

the lifting action occurring *before* instead of *after* the falling down of the wheel. In every case, however, the lifting process involves the application of additional tractive force causing energy to be stored in the mass lifted, while the falling process causes a corresponding amount of the potential energy in the mass to be converted into kinetic energy. Only a portion, however, of this energy, — that equal to the horizontal component of the pulling motion, — is usefully recovered in *producing* tractive effort, the rest being lost in consequence of the impact (shock) which occurs when the wheel "strikes bottom." As in the case of all intermittent obstructions, the tractive effort required during the lifting action passes from zero through a maximum and returns to zero. It may be considered to have a small *negative* value during the falling action. The total tractive force involved at any point of distance or of time, is equal to the algebraical sum of the instantaneous values of the individual forces concerned. The mean value, F_m, and the train resistance value (lbs. per ton) are related to and obtainable from these values in the manner already explained. Since the obstructions of the kinds under consideration all have fixed locations on the track, their total number, per unit distance, will be constant, for a given portion of track. It is therefore obvious that the total number passed over, in unit-time, by each pair of wheels, will be in proportion to the velocity of the train. In the case of a short train running at very low speed and passing over only one of these obstructions at a time, their individual effects would be more noticeable, as a sudden but brief increase, amounting to a pulsation, in the total tractive effort applied to the train. As the train is made longer (*i. e.*, as the number of wheels is increased) and also as the speed is increased, these pulsations occur more and more often, until they "coalesce," so to speak, the resultant effect of all the obstructions being then virtually the same as if they were replaced by a "continuous" obstruction. The "fictitious grade," in this case, as we can see from the preceding considerations, is one whose "percentage" will increase with the speed. It will not, however, be influenced by the length of

train, as in the case of rolling friction due to sand, but it will be practically independent of the number of wheels in the train. There are no reliable data regarding the train resistance values due to this form of rolling friction under different conditions. It is evident that these values must be greatly influenced by the condition of the track. When the track is well built, of heavy rails, and well supported (ballasted), and when it is maintained in first class condition, as is the case on the more important steam roads, the train resistance per ton, due to this kind of rolling friction must be small, and it may be even negligible. On tracks which are poorly built, with light rails, and which are in poor condition, on the other hand, it may assume considerable importance as a factor affecting the power required for traction. It was pointed out, many years ago, by Dr. P. H. Dudley, that inequalities of rail surface, causing considerable rolling friction, may be due to imperfections in the rails themselves. It was found that in some cases, owing to defects in rolling, and especially in straightening, the rails, they were "gagged" and their surface showed large numbers of minute undulations. So characteristic were these inequalities, that, in many instances, Dr. Dudley was able, from the graphical records obtained by running his "dynagraph" car over the track, to say at what mill the rails had been made. These defects have been minimized considerably in the last ten years by improvements in methods of rail manufacture, and undoubtedly, the decrease in train resistance in pounds per ton, which has taken place during this time, may be partly, though it cannot be wholly ascribed to these improvements.

The use of the term "hysteresis," in connection with train resistance was first suggested by an English engineer, Mr. A. Mallock, in the discussion of Mr. J. A. F. Aspinall's paper on "Train Resistance" before the Institution of Civil Engineers (Nov., 1901), to designate that portion of the train resistance which is due to the yielding of the rails and the ground, under the wheels. The term "track hysteresis" is a convenient one which may be used, with a slightly extended meaning, to cover, generally, all the yielding effects due to "continuous obstruc-

tions" which are elastic to any degree and which do not involve *permanent* deformation. This extension of the term includes the yielding effect in the wheel tread and the rail head, which we have already noted, as well as all yielding effects produced by the bending of the rail, or the compression of the ties, the ballasts, the ground, etc., when the deformation is only temporary and is not permanent. These effects, which have hitherto been included in the class designated by the general term "miscellaneous resistances" are, as we shall see, clearly evidences or manifestations of rolling friction.

The phenomenon of track hysteresis presents the best illustration and the most important case of rolling friction involving a "continuous obstruction" and a *uniform* fictitious grade. Its primary cause is, simply, the circumstance that the restoration

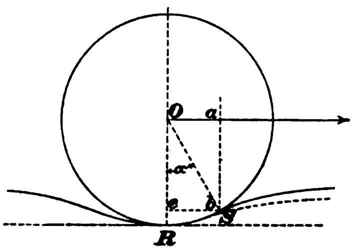


FIG. 11.

of the track to its original condition, or the "recovery" of the compressed parts of wheels, ties, rails, etc., *as a whole,* is not instantaneous, but consumes a perceptible amount of time. The result of this time-lag is (as indicated in Fig. 11) that the curve made by the portion of track *rising behind* the wheel is not the same as the curve made by the portion *falling before* the wheel, as should be the case if the parts compressed constituted a whole having elasticity and no "set." This means that the (theoretically) "recoverable" energy stored by compression, in the wheels and track, and capable of producing a tractive force which assists the motion of the car, in the manner already analyzed, is practically not all recovered. The discrepancy is easily explainable on the assumption (which appears well warranted) that during the process of compression, some of the parts, like

the ties, ballast, ground, etc., are compressed somewhat beyond the elastic limit, at the expense of additional applied tractive force, above what would be otherwise required.

The energy corresponding to this additional force is "non-recoverable," being expended in some form of friction (mostly molecular) and ultimately converted into heat. A certain amount of "set" is at the same time produced in the parts compressed beyond the elastic limit. The restoration of these parts to their original condition, after the wheel has passed, involves a second expenditure of energy, substantially equal to the first; and this energy can only come from the "recoverable" energy stored in the parts which were *not* compressed beyond the elastic limit. Thus, each time that the track is depressed momentarily, there occurs a cycle of reactions which causes the abstraction of energy from the source of the moving force and its dissipation, by friction, etc., in very much the same way as in the case of "magnetic hysteresis."

The analogy of the "effect" of this kind of hysteresis to a "fictitious grade" is referred to by Mr. Mallock, in his discussion. He speaks of the car wheel as "always virtually climbing up a hill." He further states that "in his experiments that effect had come to something like between 1 in 250 (= 0.4 %) and 1 in 400 (= 0.25 %)." He considers it a very intricate function of the velocity. The preceding figures are doubtless average results for the whole train. They have little or no significance, however, in the absence of data concerning the conditions under which the experiments referred to were made. The average effective fictitious grade, due to track hysteresis, in the case of a car or train, is affected by and depends upon so many things that the study of the yielding effects produced at a single wheel is far from sufficient to give an adequate idea of the phenomenon as a whole, or to furnish a clue to the amount of total resultant effect on the train resistance in each case. The study of the phenomenon, in the case of a single wheel, shows that it is dependent upon the pressure-density produced at each wheel, the mechanical resistance (moment of inertia) of the rail, and the resistance of the ties, ballast, earth work, etc., opposed to

compression or to deformation. When two or more wheels follow each other, as in the case of a car or train, the phenomenon is complicated by the introduction of additional variables, more especially the distance between the wheels. If, for example, the second wheel is placed as closely as possible to the first wheel, the two wheels will roll, so to speak, in a single hollow, common to them both. This means that the process of restoration of the track to its normal condition will practically begin only after the passage of the second wheel. As the distance between the two wheels is increased, there will become manifest a tendency of the rail to rise after the passage of the first wheel; this rise being, obviously, the more evident and more complete the greater the distance between the two succeeding wheels. There is, obviously, in each case, a certain minimum distance between succeeding wheels, inside of which the "recovery" of the track will not be complete and beyond which it will be complete; the hysteresis effect at any succeeding wheel in the latter case being exactly the same as at the first wheel.

We have just seen that the only energy loss involved in track hysteresis is that which is expended in producing "deformation" or "set" and in removing it. Now, in the case of two wheels placed closed together, this process of producing and removing deformation, practically occurs only once for the two wheels, instead of twice as would be the case if the second wheel were placed at a sufficiently great distance behind the first wheel. It follows, therefore, that track hysteresis will not only depend upon the total number of wheels (*i. e.*, upon the length of the train), but also upon the arrangement of these wheels, or, to be more exact, the distance between them. In the case of a long passenger car, the distance between the rear wheel of the forward truck, and the front wheel of the rear truck, is sufficiently great to allow an almost, if not entirely complete "restoration" of the track between the two trucks. This means that the hysteresis cycle will involve quite nearly, if not exactly, the same energy loss as the cycle occurring at the first truck. In practice, when passenger cars are coupled up together in trains, there is less track space between the end

wheels of two different cars than there is between the two trucks of the same car; consequently, the rise of the track between two cars is less than between the two trucks of the same car, and the hysteresis cycle for the rear truck is greater than that for the front truck, for each car, since the latter is all the time literally "following in the wake" of, or rolling in the "hollow" made by, the rear truck of the preceding car. In the case of freight cars, which are usually much shorter, the distance between the nearest wheels of front and rear trucks is smaller (the spacing between trucks being about 20 ft. for cars of 60,000 lbs. capacity), and the "restoration" or rise of the track which occurs between the two trucks is less than in the case of passenger cars (where the spacing varies from 30 to 44 ft.). Consequently, the loss by track hysteresis ought to be less in the case of freight cars than in the case of passenger cars, for the same pressure-density, or the same weight per axle. All tests show this to be true.

From the preceding study of the manner in which loss of useful energy is caused by track hysteresis, we can readily see that in order to reduce this loss it is necessary to reduce either the *number* or the *amplitude* of the hysteresis cycles produced per car or per train, at each portion of the track. The case of several wheels rolling in the same "hollow" suggests the ideal condition for this purpose to be one where the whole train weight is so distributed on or received by the track that there is only one "hollow" in the entire portion of the track covered by the train, and, consequently, only a single hysteresis cycle is produced by the passage of that train. The decrease in train resistance effected in the last few years may be ascribed principally to the efforts made to realize this ideal condition in actual practice. The highest credit is due, in this connection, to Dr. P. H. Dudley, whose name should be at the very head of the list of investigators of railroad track phenomena and problems who have done the most, directly or indirectly, to bring about this valuable result.

(Omission will be made, for lack of space, of an extended reference, illustrated with numerous lantern slides, made, at

this point, in the lecture, to Dr. Dudley and his valuable work, including a description of his "dynagraph" car, for automatically "inspecting" railroad tracks and graphically recording all details of their condition at all points, also his "stremmatograph" for measuring the deflections and the fibre strains produced in the rail, at any point, by the passage of a given train, also a summary of the improvements in "comparative condition of tracks," per year, from 1881 to 1902, resulting from scientific methods of rail design and track construction.)

Dr. Dudley had noticed, nearly twenty-five years ago, in making a series of experiments on train resistance on several roads, that the train resistance decreased sensibly when running over new rails, after passing over old worn rails, although the topographical conditions of the line remained substantially the same. These experiments (made on rails 4 to 4.5 inches high and weighing from 56 to 63 lbs. per yard when new), indicated the presence of yielding effects in the track which increased as the rails became worn. It was soon afterward noted by Dr. Dudley that even when these rails (which were the "standard" rails in 1880 and for some years afterward) were new, and even when the greatest care was taken in "surfacing" the track, the yielding effect was still too great and too much "localized," that is to say, the mechanical stiffness (moment of inertia) of the track was insufficient to cause the wheel loads to be distributed over a great enough length of rail to make a smooth track. This led Dr. Dudley to make a systematic comprehensive study of the physical and mechanical principles involved in these yielding effects. He appears to have been the first to recognize the important analogy between a loaded track and a girder beam which is not uniformly loaded. He noticed and studied carefully the fact that each truck of a car makes a "general" depression in the track, by its total weight, "specific" or "individual" deflections being at the same time produced under each wheel; the conditions being analogous to a girder whose load is applied at a few points. It being impracticable to make material changes in the loads or their manner of application to the track by changing the number or the spacing of the car wheels, Dr.

Dudley sought to reduce the deflections by increasing the stiffness of the rails. This led, about 1883, to the design and the introduction into use on some roads, of a rail 5 inches high weighing 80 lbs. per yard, and having a mechanical stiffness 60 to 70 percent greater than that of the 4.5 inch rail; the consequence being that the yielding effects (termed "deflections" by Dr. Dudley) were diminished to less than half the previous amount, as shown by the dynagraph car diagrams. The possibility of increasing the weight and the power of locomotives, and of handling heavier trains, on heavier rails, stimulated their adoption by many roads, and, by 1890, their use had become quite general on the Eastern lines of this country. The maximum axle load, which, in 1880 and for several years after, had been limited to 27,500 lbs., began to be increased about 1886, and, by 1890, it had reached 40,000 lbs. Considerable study and many experiments were devoted, in the meantime, by Dr. Dudley, to the important object of further increasing the "stiffness" of a rail without increasing its weight (on which its *cost* depends) by a different distribution of the metal, or by changing the "cross-section" of the rail, so as to increase its moment of inertia. The result was the 5.125 in. "80-lb." rail, the principal feature of which was a wider and flatter head. The importance of designing rails so as to secure the maximum stiffness for a given weight was emphasized by Dr. Dudley in some very instructive remarks made by him before the American Institute of Electrical Engineers, Feb. 24, 1891 (Vol. VIII, pp. 82, 83 and 86–88). The fact that Dr. Dudley had in contemplation the use of still stiffer rails than the 5.125 in. "80-lb." rail, at this time, is shown by his reference to some 95-lb. rails, "which he had just made for a road, which will be very much stiffer than the 80-lb. rails," and also his reference to his design of a 105-lb. rail "which are nearly 100 % stiffer than the 80-lb. rails." He states, incidentally, that "All trials show a very material reduction in train resistance with the heavy rails, as we increase the stiffness." The heaviest and stiffest rail in regular use at the present time is the 6-inch 100-lb. rail, which first came into use as far back as 1892. The increase in

the stiffness of the rails has permitted a still further increase in the maximum locomotive axle load, which is now 50,000 lbs. and even more.

In the case of the larger freight cars, of capacity ranging from 80,000 lbs. to 100,000 lbs., the wheel-base of the trucks has been increased and the spacing between the trucks has been decreased. Dr. Dudley's investigations show that with freight trains made up of such cars, running on very heavy and stiff rails, there is practically only one general, continuous, depression of the rails, sleepers, ballast, and road-bed, which extends from the front pilot-wheel of the locomotive to the last wheel of the "caboose" at the rear end of the train. There is still evidence of the "specific" or "individual" deflections under the wheels, but these are very small. The track forms a practically continuous girder which is "restrained," or, as Dr. Dudley prefers, "*constrained*," by the stiffness itself of the rail, to such an extent that the rise or "restoration" of the rail surface, in the unloaded portions, between the wheels, is greatly restricted. The practical consequence of this constrained condition is that the passage of the entire freight train causes only one hysteresis cycle of the full amplitude. The small "specific" deflections just noted produce only minute, relatively insignificant cycles, which might be termed "sub-cycles." These occasion a very small energy loss, as compared with the principal cycle. The ideal condition previously referred to is thus found to be realized, to a great extent, in practice, in such cases. The train resistance, for these cases, as due to track hysteresis, may, therefore, be regarded as approximately constant *per train* somewhat like that due to "sand"; the result being that it will be relatively small in the case of long and heavy freight trains. According to Dr. Dudley, the train resistance for long and heavy freight trains, which, in the days of 4.5 inch rails, ranged from 7 to 8 lbs. per ton, is now only about half this amount. This reduction of train resistance is not all due to the diminution of track hysteresis, however. The increased pressure on the journal bearings, as the result of greater weights per axle, causes the coefficient of journal friction to be diminished, as we

have already seen. The increase in the *length* of freight trains may also be a factor here, though of less importance, in the reduction of the train resistance.

In the case of passenger cars, according to Dr. Dudley, the portion of the rail which happens to be in the center of the wheel spacing (*i. e.* under the middle of the car), is generally "relieved" of strain, partly or wholly, according to the length of the car and of this spacing. Consequently, the depression under the whole train is not a general or a continuous one, as in the case of freight cars; and the loss of power by track hysteresis is much greater, being, in this case, practically proportional with the number of *cars*. This accounts, in part, for the higher train resistance found in the case of passenger trains, on steam roads.

It is evident that the same "formula" for rolling friction (considered alone), would not fit the two cases just noted, without being modified. Indeed, the extent to which the three principal forms of rolling friction vary, and, especially, the relatively great number of circumstances affecting or influencing the variations, indicate the great difficulty of devising a single, simple, yet sufficiently comprehensive formula which will be applicable to all cases.

(*To be continued.*)

THE INDUCTION MOTOR.

By C. A. Adams, Assistant Professor of Electrical Engineering, Harvard University.

(Continued from November, 1904.)

III.

In the second part of this article the vector diagram of the Induction Motor was developed and explained in some detail. The writer wishes again to emphasize the importance of a thorough understanding of this diagram, and a thorough appreciation of its limitations. These arise from the assumptions made at the outset, which were chiefly to the effect that all currents, e. m. f.'s, and peripheral current and flux distributions were sinusoidal.

The sinusoidal current distribution assumes a large number of phases, which is impracticable, three being the practical limit. With this number the active conductors of a single-phase belt * are usually distributed in several slots, the peripheral width of the belt varying from about 2 inches in a 60-cycle motor, to 4 inches in a 25-cycle motor. Thus, since the peripheral current density is constant at any instant over a given belt, the current distribution does not vary gradually from point to point, but by steps of considerable size.

If the secondary has a two- or a three-phase winding, as is usually the case in large motors and frequently in small ones, the partial overlapping of a secondary phase belt on two primary phase belts results in local unbalanced m. m. f.'s, due to the currents I_2 and I'_1, even assuming that the r. m. s. and average values of these currents are equal. This disturbance may be classed in general under *differential action*, due to the width of a single phase-belt and the consequent fact that the action in different parts of that belt is at times in opposite

* The conductors per phase and per pole.

directions and thus wasteful. This differential action may relate to the m. m. f. (as above) or torque of the current in, or to the e. m. f. generated by the different parts of a single belt. The latter is usually taken account of in the calculation of induction motors, by the introduction of a constant less than unity, which will be hereinafter called the *differential factor*; but heretofore no account has been taken of the differential action between the currents I_2 and I'_1, as above noted. If the secondary is of the squirrel cage type, this last is negligible as is that of e. m. f. generation in the secondary, owing to the fact that each secondary conductor is to all intents and purposes an independent phase, and the width of the phase-belt is thus reduced to a minimum. The presence of teeth and the distortion of impressed wave shape may also introduce considerable complications.

These points should be borne in mind in connection with the following mathematical analysis, which is based upon the diagram and its underlying assumptions, since a course of reasoning carried out by mathematics does not differ from one carried out by any other mode of expression; the result contains no information not contained in the premises, but merely puts that information into a more useful form. Thus no matter how completely and exactly the mathematical transformations may be made, the accuracy of the result is limited by the legitimacy of the assumptions upon which is based the method of analysis.

This point is emphasized because of the frequency of its neglect and the consequent disappointment when comparison is made between calculated and observed results.

Algebraic Analysis of the Relations Existing between the Several Variables and Constants of the Induction Motor.

This analysis reveals nothing not implied in the vector diagram, as it is merely an algebraic statement and transformation of the relations there shown graphically. Some of the results are however in a much more convenient form.

EQUIVALENT CIRCUIT SCHEME.

A little consideration will show that the equivalent circuit scheme represented by the induction motor diagram is that of Fig. 24. Thus the mutual flux Φ is proportional to E'_1, and I_0 is approximately proportional to Φ; I_0 may then be considered as being produced by the e. m. f. E'_1 in a separate circuit of resistance r_0 and reactance x_0 or of conductance g_0 and susceptance b_0; r_0 and g_0 relate to the energy component of I_0 and are determined by the core losses, while x_0 and b_0 relate to the wattless or magnetizing component and are determined by the reluctance of the main magnetic circuit. As the reluctance of this main path is approximately constant, so are x_0 and b_0. If r_0 and g_0 were constant, the energy component of I_0 would be proportional to E'_1 and the core losses proportional to the square of E'_1 or of Φ; but since the core losses are more nearly proportional to the 1.6th power of Φ, it is evident that the energy component of I_0 increases a little less rapidly than E'_1 and that r_0 and g_0 decrease slightly with increasing flux.

However, since E' and Φ are nearly constant during the normal operation of any given motor, and since this energy component is a small part of the whole current, the assumption that

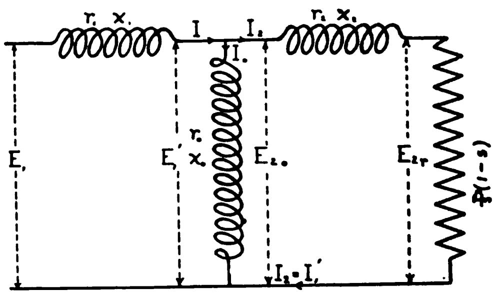


FIG. 24.

r_0 and g_0 are constant will introduce an exceedingly small error.

It has already been shown that the secondary current I_2, or its equivalent I'_1, is the same as would be produced by the e. m. f.

E_{20} $(=E'_1)$ in a circuit of resistance, $\frac{1}{s}\, r_2$, and reactance x_2;* also that this circuit may be subdivided into two portions, one of resistance r_2 and reactance x_2, and the other of non-inductive resistance $\left(\frac{1}{s} - 1\right) r_2$, which represents the load and varies with the slip. From this standpoint the induction motor is exactly analogous to an ordinary transformer with a variable non-inductive resistance in the external secondary circuit.

The two currents I_0 and I_2 $(= I'_1)$ which are produced by the same e. m. f. E'_1, and which combine to make the total primary current I_1, may thus be considered as flowing in two parallel circuits branched off from the main primary circuit as in Fig. 24.

With this introduction, the algebraic statement follows naturally.

Consider first the secondary and exciting circuits in parallel; their equivalent resistance and reactance are found in the ordinary manner, Fig. 25.

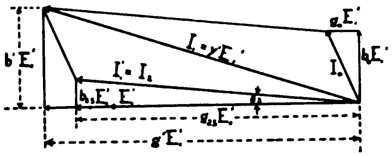


FIG. 25.

$g_0 = \frac{r_0}{z_0^2}$ is the exciting conductance;

$b_0 = \frac{x_0}{z_0^2}$ is the exciting susceptance;

$y_0 = \sqrt{g_0^2 + b_0^2} = \frac{1}{z_0}$ is the exciting admittance;

$g_{2s} = \frac{r_{2s}}{z_{2s}^2}$ is the total secondary conductance, where

* As in Part II it is here assumed throughout that the secondary quantities are reduced to primary turns.

$r_{2s} = \frac{r_2}{s}$ is the total equivalent secondary resistance, and

$z_{2s} = \sqrt{r_{2s}^2 + x_2^2}$.

$b_{2s} = \frac{x_2}{z_{2s}^2}$ is the secondary susceptance, and

$y_{2s} = \sqrt{g_{2s}^2 + b_{2s}^2} = \frac{1}{z_{2s}}$ is the secondary admittance.

Designate the equivalent constants for these two circuits in parallel by r', x', g', b', etc. Then

$$\left.\begin{aligned} g' &= g_0 + g_{2s} \\ b' &= b_0 + b_{2s} \\ y' &= \sqrt{g'^2 + b'^2} \end{aligned}\right\} \quad . \quad . \quad . \quad . \quad . \quad (28)$$

$$\left.\begin{aligned} r' &= \frac{g'}{y'^2} = \frac{r_0 z_{2s}^2 + r_{2s} z_0^2}{(r_0 + r_{2s})^2 + (x_0 + x_2)^2} \\ x' &= \frac{b'}{y'^2} = \frac{x_0 z_{2s}^2 + x_2 z_0^2}{(r_0 + r_{2s})^2 + (x_0 + x_2)^2} \\ z' &= \sqrt{r'^2 + x'^2} \end{aligned}\right\} \quad . \quad . \quad (29)$$

Then the total equivalent constants for the whole motor are (see Fig. 26) —

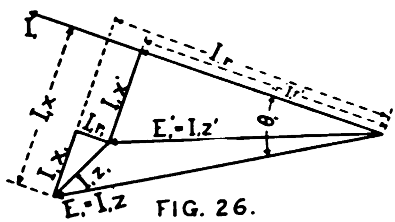


FIG. 26.

$$\left.\begin{aligned} r &= r_1 + r' \\ x &= x_1 + x' \\ z &= \sqrt{r^2 + x^2} \end{aligned}\right\} \quad . \quad . \quad . \quad . \quad . \quad . \quad (30)$$

It will aid much in obtaining a grasp of the equations that follow, to connect clearly each of the above constants and each of the equations with the circuit scheme of Fig. 24.

The more important of these constants are plotted against s for a typical motor, in Fig. 27.

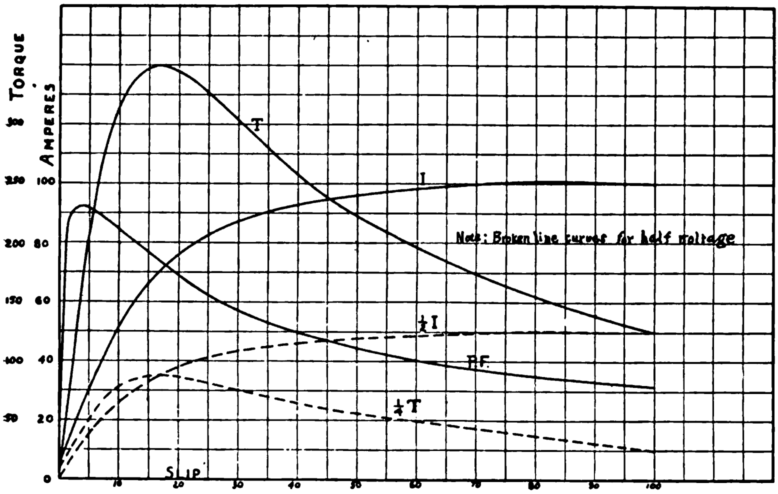


FIG. 27

The *primary current* is then —

$$I_1 = \frac{E'_1}{z'} = \frac{E_1}{z} \qquad (31)$$

The power factor is —

$$\cos\theta_1 = \frac{r}{z} \qquad (32)$$

From Fig. 26 —

$$E'_1 = E_{2\,o} = E_1 \frac{z'}{z} \qquad (33)$$

Then —

$$I_2 = I'_1 = \frac{E_{2\,o}}{z_{2\,s}} = E_1 \frac{z'}{z z_{2\,s}} \qquad (34)$$

and

$$I_0 = \frac{E'_1}{z_0} = E_1 \frac{z'}{z z_0} \qquad (35)$$

The *input* is —

$$P_1 = p\, E_1\, I_1 \cos\theta_1 = p\, \frac{E_1^2}{z^2}\, r \qquad (36)$$

where p is the number of phases.

From eq. (26) page 223, the *output* (including friction) is —

$$P_2 = p\, E_2{}^2{}_0\, \frac{(1-s)\, r_{2s}}{r_{2s}^2 + x_2^2} = p\, E^2{}_1\, \frac{z'^2}{z^2}\, \frac{(1-s)\, r_{2s}}{z_{2s}^2} \quad . \qquad (37)$$

The *torque* * is —

$$T = \frac{P_2}{\text{angular velocity}} = \frac{pp'}{2\pi n}\, E^2{}_1\, \frac{z'^2}{z^2}\, \frac{r_{2s}}{z_{2s}^2} \quad . \quad . \qquad (38)$$

and the *efficiency* (friction neglected) is —

$$\frac{P_2}{P^1} = (1-s)\, \frac{z'^2}{z_{2s}^2}\, \frac{r_{2s}}{r} \quad . \quad . \quad . \quad . \quad . \quad . \qquad (39)$$

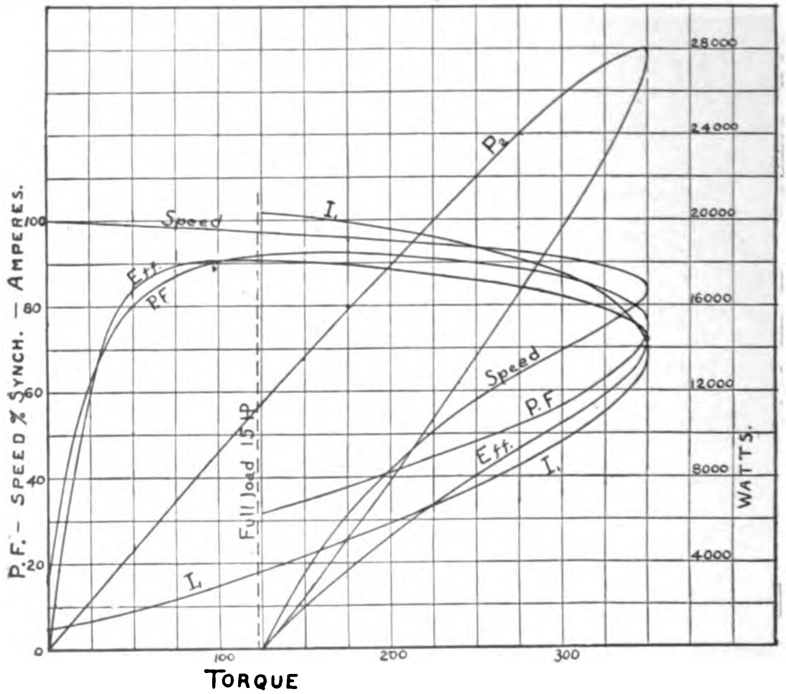


FIG. 28.

* The unit of torque here used is that of the practical electromagnetic system, corresponding to the volt, ampere, watt, etc. Unfortunately, there is no accepted name for this unit. It is equal to 10^7 dyne centimeters, .102 Kg. meters, or .737 lb. ft. The torque of eq. 27 is expressed in these same units, *not* in synchronous watts.

Thus, for any given value of s, the *input*, *output*, and *torque* are proportional to the square of the impressed e. m. f.; the *power factor* and *efficiency* are independent of it; and the currents are proportional to it. This is illustrated by the curves of Fig. 27 for a 15–H. P. motor, with the following constants: $r_0 = 8$, $x_0 = 50$, $r_1 = r_2 = .4$, $x_1 = x_2 = 1.2$. The solid curves correspond to the normal voltage 440, and the broken curves to 220 volts.

In Fig. 28 the same curves (for normal E_1) are plotted against the torque. This is a more common form of plotting.

The motor is star connected, so that the volts per phase in the two cases are $E_1 = 254$ and $E_1 = 127$ respectively.

The torque curves for full and half voltage show clearly the importance of holding up the impressed e. m. t., (unless the margin between full load and breakdown is normally a large one).

Above are all the important characters of the Induction Motor expressed in terms of its constants,* of the slip and of the impressed e. m. f.; or since the latter is usually constant, the characteristics are expressed as functions of the slip, s, or of 1-s which is the speed in percent of synchronous speed.

When the equations are expanded, it will be found that the induction motor variables are for the most part fairly complicated functions of the slip, and that the calculation of the characteristic curves for a given set of constants is a considerable task.

CALCULATION.

Nevertheless it is recommended that for purposes of calculation the formulae be used in their complete form; for although

* It has already been noted that g_0, the exciting conductance, is not strictly constant, and it will be shown later that the leakage reactances vary somewhat from no load to full load, owing to the saturation of the iron portions of the leakage paths. The reluctance of the main flux path also increases slightly with the load, due to the saturation of the tooth corners and sometimes of the teeth; so that b_0 and x_0 are not strictly constant. Moreover, the change in temperature of the windings cause considerable changes in the resistances of those windings, r_1 and r_2.

certain approximations can be made without seriously impairing the accuracy of the results for special cases, in others the errors may be considerable. The inherent errors already mentioned are sufficient, without adding unnecessary ones.

For *approximate calculations* a graphical method will be given later.

ANALYSIS.

For purpose of analysis the complete diagram, Fig. 22, will serve very well in some cases, *e. g.*, in the investigation of the manner in which the several constants affect the power-factor or the current; but there are other important points best considered with the aid of approximate equations.

APPROXIMATE EQUATIONS.

The most effective approximation for this purpose is to neglect the effect of I_0 upon the drop of voltage between E_1 and E'_1. Then equation 33 becomes —

$$E'_1 = E_{2\,o} = E_1 \frac{z_{2\,s}}{z_s} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \qquad (40)$$

where $z_s = \sqrt{r^2_s + x^2_s}$, $r_s = r_1 + r_{2\,s}$, and $x_s = x_1 + x_2$.

It is obvious that z_s is the series impedance of the primary and secondary circuits, the exciting circuit being neglected. A glance at the diagram, Fig. 22, will show that with ordinary constants, that part of the primary impedance drop due to I_0 is approximately in phase with E'_1 and contributes largely to the numerical difference $E_1 - E'_1$. The value of E'_1 as given by equation 38 is from 2% to 5% too large throughout the normal range of operation. Moreover, since E'_1 enters as the square in P_2 and T, this error will be doubled; it is therefore not at all negligible from the standpoint of *calculation*, although it serves well for a rough analysis.

Substituting in equation 37 gives —

$$P_2 = p\,\frac{E^2_1}{z^2_s}\,r_{2s}\,(1-s) = p\,E^2_1\,\frac{\frac{r^2}{s}(1-s)}{\left(r_1 + \frac{r_2}{s}\right)^2 + (x_1 + x_2)^2} \qquad (41)$$

where $\frac{E^2_1}{z^2_s}$ is the square of the current that would flow when the exciting circuit is omitted, and $\frac{r_2}{s}(1-s)$ is the equivalent load resistance (see Fig. 24).

Maximum Output.

Placing $\frac{dP_2}{ds} = 0$ gives —

$$s = \frac{r_2}{r_2 + \sqrt{(r_1 + r_2)^2 + (x_1 + x_2)^2}} \quad . \quad . \qquad (42)$$

where $\sqrt{(r_1 + r_2)^2 + (x_1 + x_2)^2}$ is the series impedance of primary and secondary when $s = 1$, *i. e.* at standstill.

Then the maximum output is —

$$P_{2\,max} = \frac{p\,E^2_1}{2[(r_1 + r_2) + \sqrt{(r_1 + r_2)^2 + (x_1 + x_2)^2}]} \qquad (43)$$

Referring to equations 42 and 43, and remembering that ordinarily r_2 and $(r_1 + r_2)$ are small when compared with $\sqrt{(r_1 + r_2)^2 + (x_1 + x_2)^2}$, it appears that —

The slip at which the maximum output occurs is roughly proportional to r_2, and inversely to $\sqrt{(r_1 + r_2)^2 + (x_1 + x_2)^2}$; also that the maximum output is roughly inversely proportional to $\sqrt{(r_1 + r_2)^2 + (x_1 + x_2)^2}$.

Substituting (40) in (38), gives —

$$T = \frac{pp'}{2\pi n}\,E'^2_1\,\frac{r_{2s}}{z^2_{2s}} = \frac{pp'}{2\pi n}\,E^2_1\,\frac{\frac{r^2}{s}}{\left(r_1 + \frac{r_2}{s}\right)^2 + (x_1 + x_2)^2} \qquad (44)$$

This is the same as equation (11), page 79, except that here the primary drop of pressure is partly taken account of, as indi-

cated by the presence of r_1 and x_1. Its analysis will also yield essentially the same results as regards the shape of the speed-torque curve.

Maximum Torque.

Placing $\frac{dT}{ds} = o$, gives —

$$s = \frac{r_2}{\sqrt{r_1^2 + (x_1 + x_2)^2}} \quad . \quad . \quad . \quad . \quad (45)$$

and the maximum torque is —

$$T_{max.} = \frac{pp'}{2\pi n} \frac{E_1^2}{2(r_1 + \sqrt{r_1^2 + (x_1 + x_2)^2})} \quad . \quad . \quad (46)$$

Thus *the slip at which the maximum torque occurs is proportional to* r_2, (as in equation 14 where r_1 and x_1 were neglected) *and approximately inversely proportional to the total leakage reactance,* $x_1 + x_2$. Also *the maximum torque is independent of* r_2 (in equation 15 and Fig. 16) *and approximately inversely proportional to the total leakage reactance,* since r_1 is small compared to $x_1 + x_2$.

Starting Torque.

Placing $s = 1$ in equation 44,

$$T_0 = \frac{pp'}{2\pi n} E_1^2 \frac{r_2}{(r_1 + r_2)^2 + (x_1 + x_2)^2} \quad . \quad . \quad . \quad (47)$$

which, *for small values of* r_2, *is approximately proportional to* r_2 *and inversely to* $(x_1 + x_2)^2$. This last is a very important point and will be considered below in connection with methods of starting.

Maximum Starting Torque.

The value of r_2 which makes T_0 a maximum is obtained by placing $s_{Tmax.} = o$ in equation 45. It is —

$$r_2 \text{ (for max. starting torque)} = \sqrt{r_1^2 + (x_1 + x_2)^2} \qquad (48)$$

and the maximum starting torque is the same as that of equation 46.

STARTING CURRENT.

Neglecting the exciting current,* the starting current is —

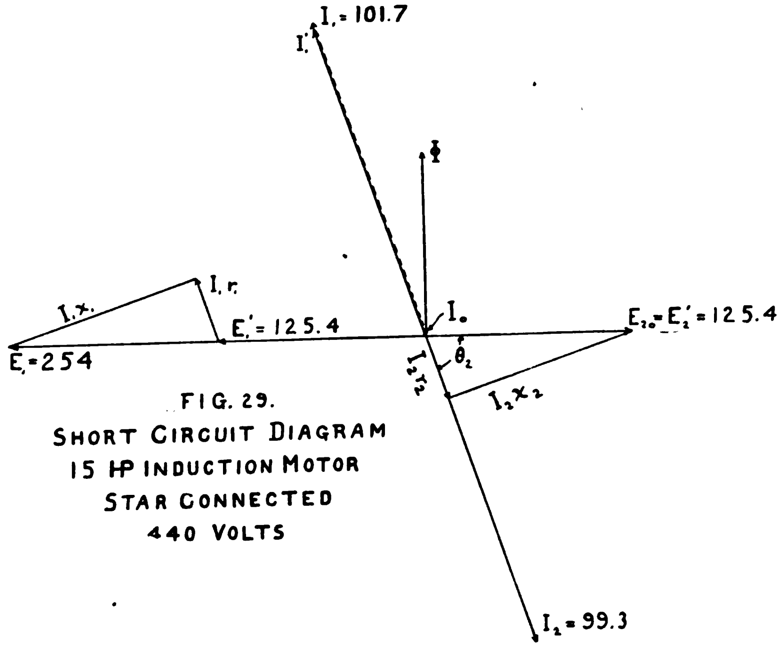


FIG. 29.
SHORT CIRCUIT DIAGRAM
15 HP INDUCTION MOTOR
STAR CONNECTED
440 VOLTS

$$I_{1\,0} = \frac{E_1}{\sqrt{(r_2 + r_2)^2 + (x_1 + x_2)^2}} \quad . \quad . \quad . \quad (49)$$

Then —

$$T_0 = \frac{pp'}{2\pi n} r_2 I_1{}^2{}_0 = \frac{pp'}{2\pi n} E_1 I_{1\,0} \frac{r_2}{\sqrt{(r_1 + r_2)^2 + (x_1 + x_2)^2}} \quad (50)$$

Since I_0 was neglected, $I_{1\,0}$ is the secondary as well as the primary starting current, and the starting torque is thus propor-

* As the slip increases from no load, I'_1 increases and I_0 decreases (since the primary drop increases and E'_1 decreases accordingly). In a good motor, the exciting current at standstill is only about 3 % of the load current. The decrease in I_0 also reduces the error introduced by the approximation of equation 40, this error being relatively small at standstill, when E'_1 and I_0 have usually less than half of their no load values. The standstill or short-circuit diagram for the motor of Figs. 27 and 28 is drawn to scale in Fig. 29.

tional to the secondary copper loss at standstill. But this might have been predicted, since the starting torque is due only to the power transmitted across the gap to the secondary. In some motors the secondary core loss at standstill is considerable, which may add appreciably to the starting torque.

Efficiency of Starting Torque.

One of the most serious charges against the induction motor is that its starting current is inherently large as compared with the starting torque. The reason for this is two-fold: first, the torque-producing effect * of the secondary current is reduced by its lag behind its e. m. f. $E_{2\,o}$, and in the ratio $\cos\ \theta_2 = \dfrac{r_2}{\sqrt{r_2 + x_2^2}}$; second, the flux upon which the current reacts to produce the torque, and which is proportional to and represented by $E_{2\,o}\ (= E'_1)$, is much reduced, owing to the drop in the primary winding, due to r_1 and x_1.

In the ideally perfect motor, without losses or leakage, both of these causes are absent since $r_1 = x_1 = x_2 = o$, $E_{2\,o} = E^1$ and $\cos\ \theta_2 = 1$.

Then the starting torque would be (see eq. 47) —

$$T_{oo} = \frac{pp'}{2\pi n}\frac{E_1^2}{r_2} = \frac{pp'}{2\pi n} E_1 I_{1\,oo},$$

or, the starting torque per ampere for the ideal motor is —

$$\frac{T_{oo}}{I_{1\,oo}} = \frac{pp'}{2\pi n} E_1,$$

and for the real motor (see eq. 50) —

$$\frac{T_o}{I_{1\,o}} = \frac{pp'}{2\pi n} E_1 \frac{r_2}{\sqrt{(r_1 + r_2)^2 + (x_1 + x_2)^2}}$$

The ratio of the real to the ideal may then be defined as the *efficiency of starting torque*, and is —

$$Eff_{To} = \frac{r_2}{\sqrt{(r_1 + r_2)^2 + (x_1 + x_2)^2}} \quad . \quad . \quad . \quad (51)$$

This may serve as a basis for comparing the starting qualities

* See Part I, pages 75–81, April, 1904.

of the induction motor with those of the d. c. motor, in which, with the same assumption (exciting current neglected), the starting-torque efficiency is nearly 100 %. It cannot be high in the case of the induction motor without separate starting resistance; in that case it frequently exceeds 90 %. With squirrel cage motors it varies from 10 % to 40 %. The latter is unusual and can be obtained only at the sacrifice of efficiency and speed regulation, *i. e.* by making r_2 large.

It will be interesting to investigate the *starting-torque efficiency* for the case of *maximum starting-torque*, *i. e.* with $r_2 = \sqrt{r_1^2 + (x_1 + x_2)^2}$ *, (see eq. 48). Substituting this in eq. 51, gives —

$$Eff_{\text{To max.}} = .707 \sqrt{\frac{\sqrt{r_1^2 + (x_1 + x_2)^2}}{r_1 + \sqrt{r_1^2 + (x_1 + x_2)^2}}} \quad . \quad . \qquad (52)$$

If $(x_1 + x_2)$ is relatively very large, this approaches the value .707, and if $(x_1 + x_2)$ is relatively very small, it approaches the value .5. For normal proportions it is not far from .64, and is independent of r_2. The reason why the larger values of $(x_1 + x_2)$ give larger values in eq. 52 is that with the earlier breakdown torque (see Fig. 17, April, '04), a larger value of r_2 is required to bring the maximum torque at standstill.

Undesirability of Leakage.

Referring now to equations 47 and 51, it will appear that one of the chief obstacles to high starting torque and high starting-torque efficiency is the leakage reactance, $x_1 + x_2$; and although it also has a very undesirable effect upon other characteristics of operation (*e. g.*, power factor), its undesirability cannot be better illustrated than in connection with the simpler methods of starting squirrel cage motors.

The Starting of Squirrel Cage Motors.

Owing to the rugged simplicity of this type of induction motor, it should be used wherever possible; but if it is thrown

* This condition is practically impossible without separate starting resistance.

directly on the line at starting, it takes a current from 3 to 8 times the full load running current and at such a low power factor that, except with very small motors, the drop along the line (and even in the generator unless it be relatively very large) is excessive and very undesirable. To avoid this, a compensator (or auto-transformer) is employed to supply the motor at reduced voltage; but the starting torque is proportional to the square of the voltage, and if the latter be reduced one-half, T_0 will be reduced to one-fourth of its full-voltage value.

Suppose the motor in question is that whose speed torque curve is shown in Fig. 30, No. 1, its full voltage starting torque is less than one-third of the normal running torque, so that the starting torque for half voltage will be only 8% of the full load

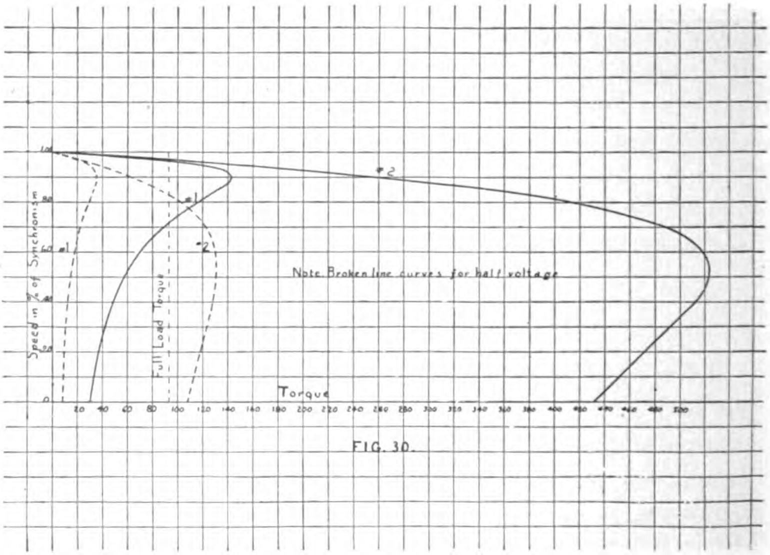


FIG. 30.

torque, which is only permissible in a motor which is never required to start under any load whatever. A tight belt would alone prevent its starting without assistance.

The starting current, even with this low torque, is more than that for full load.

Curve No. 2 shows a motor with the same constants except

as regards leakage, the leakage reactance being one-fifth of that of No. 1.

A comparison of these two motors, for starting, is made in Table I, which speaks for itself.

Table I.

	Full voltage.			¾ Full voltage.			½ Full voltage.			⅓ Full voltage.		
Motor	T_0	I_{10}	I	T_0	I_{10}	I	T_0	I_{10}	I	T_0	I_{10}	I
No. 1	.32	2.5	2.5	.18	1.88	1.4	.08	1.25	.625	.035	.83	.28
No. 2	4.7	10.2	10.2	2.65	7.65	5.7	1.18	5.12	.55	.52	3.4	1.14

T_0 is the starting torque, I_{10} the starting current, and I is the current taken from the line, all in percent of full load running values.

The two motors are extremes, but not impossible. They illustrate the *necessity* of low reactance in squirrel cage motors,

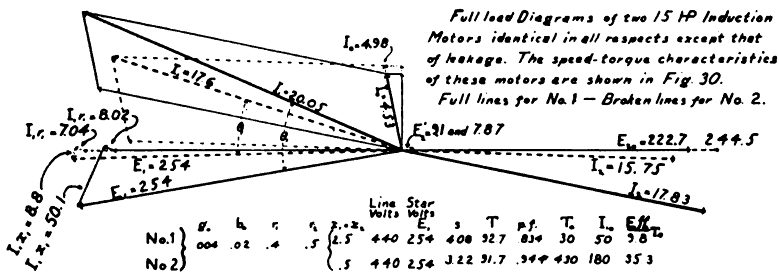


FIG. 31

and the fact that with a very low reactance this type of motor will start with more than full torque when taking only 2.5 times full current from the line, or with one-half full torque when taking only a little more than full current from the line. Such a motor is larger and more expensive to build, has a larger exciting current and a somewhat lower power factor on that account; but the sacrifice is well worth the gain in simplicity and robustness.

This subject will be further discussed under "Design," in a later installment of this article.

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Editorial.

FOR the purpose of promoting the general knowledge and discussion of Engineering subjects together with the social inter-

course of students, there have been organized since 1894 the Harvard Engineering Society, and the Harvard Civil, Electrical, Mechanical, and Mining Clubs. The membership of these clubs is open to all who are interested, excepting that Freshmen may not join the Engineering Society or the Civil Club.

Men wishing to join the Engineering Society, the Civil Club, or the Electrical Club should hand their names to the secretaries of these organizations.

To become a member of the Mechanical Club it is necessary only to pay dues to the treasurer. To join the Mining Club, one should pay dues to the secretary at a regular meeting of the club.

Harvard Engineering Society (1894).

Membership, 160. Annual dues, $1.50.

Subscription to the Harvard Engineering Journal together with membership in the Society, $2.00 yearly.

Meetings monthly. Refreshments.

President, Roy Bullen, 11 Perkins Hall.
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Open to men interested in Mining, Metallurgy, or Economic Geology.

President, James D. Tew, 44 Dunster.
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Our Societies are comparable to the organizations which mean so much to Engineers in practical life. They are valuable to the members both from the good fellowship which they develop, and from the speakers with whom they are privileged. At their meetings a student meets men with common interests, men with whom he will come in contact during later life. The meetings give also the chance to hear and to know personally men who stand high in their professions.

In several of the clubs frequent discussions and papers by students themselves make them still more valuable.

Graduate Notes.

Mr. A. S. Hawks, M. E. '00, has recently come to the Scientific School as assistant in Engineering. Previously he had been engineer of the Conrey Placer Mining Co. of Virginia City, Montana, where a placer gold mine was worked by dredging machinery. After leaving Montana, Mr. Hawks was in the erecting shops of the Nordberg Mfg. Co. Milwaukee, and in the gas engine departments of the Allis-

Chalmers Co. and of the Power Mining Machinery Co., Cudahay, Wis., as checking and designing draftsman.

Moses King, Jr., '04, is working in the testing room of the Western Electric Co., New York City. Home address, 2 West 88th St., New York, N. Y.

John Howe Hall, '03, is now in the Crucible Steel Department of the Bethlehem Steel Co. Home address, 505 Cherokee St., So. Bethlehem, Pa.

Mr. J. A. Moyer, '99, is in charge of calculations for experimental work for the General Electric Co. at Lynn, Mass. Mr. Moyer was formerly an instructor at the Lawrence Scientific School and an associate editor of the JOURNAL.

Harvard Engineering Camp.

Through the generosity of a friend of the University, the Engineering Camp at Squam Lake, N. H., has been able to purchase about two hundred acres of very desirable land, adjacent to the old property. This, with the small ponds at the foot of Red Hill and elsewhere, together with hydrographic work in Squam Lake will be the basis of next year's work in surveying.

Since last summer, the camp has been improved by better sanitary arrangements, by broader piazzas, for out-of-door dining, with railings and comfortable benches, and by more ample accommodations in the lecture rooms. The launch also has been remodelled, and will be run by steam, instead of naphtha.

Copies of the map completed last year may be obtained of C. H. Paige, 114 Pierce Hall. The map includes all of Squam Lake and the roads between Chick's Corner, Meredith, and Ashland.

Pen and Brush Club.

The Pen and Brush Club was founded in 1894 by members of the Class of 1896, its object being to promote social intercourse among its members and to encourage a keener interest in matters relating to architecture and the other fine arts. The members are drawn from the department of Architecture

at the University but other men in the University deeply interested in art and architecture are also eligible. Any student in the department who does promising work in his first year may be elected a member during that year while others, who are upper classmen, are elected from time to time. The dues are $5.00 per year. There is no initiation fee, candidates for membership being required to undergo an initiation which usually takes the form of making a drawing, painting, or something similar.

Interest in architecture is encouraged, among other ways, by means of a series of lectures by men distinguished in the profession and by sketch and finished drawing competitions among the members of the club, liberal cash prizes being awarded. The Club holds also, during the latter part of each college year, an exhibition of original work of club members. The exhibits are of two classes, namely Architectural Design, and miscellaneous drawings, paintings, etc. Medals are awarded to the winners in each class. Mr. H. D. Whitfield, '98, of New York City, a former president of the club, has recently presented a bronze medal to be competed for annually by members of the club. The annual dinner generally brings together, not only the present members of the club but past members as well.

The Department of Architecture has given to the club the use of a small room in Nelson Robinson Jr. Hall where the meetings are held. Among the periodicals there for the use of members are: The International Studio, Masters in Art, Jugend, the Harvard Crimson and the Harvard Lampoon.

Architectural Notes.

It was the privilege of many who were interested in architecture and landscape architecture to listen recently to Mr. Frank Miles Day of Philadelphia, a prominent architect, who spoke in Robinson Hall, under the auspices of the Pen and Brush Club, on the question of Municipal Improvements in this country.

The cities of St. Louis, Minneapolis and St. Paul, Cleveland, Buffalo, Washington and New York came under consideration

and the masterly solution by different architects of the problems in the placing of the public buildings and the developing of the park systems were shown by lantern slides and explained.

The "programme" at Cleveland was particularly impressive in its scope, involving not only the placing of the public buildings but a railroad terminal and accommodation for some of the largest shipping business in the country if not in the world.

It was inspiring to hear that this development was the result of the splendid civic common sense of the public authorities influenced by the practical idealism of the architects. Members of the architectural club in that city it is understood first made the suggestion and worked out the schemes, one of which was later developed.

The case of Buffalo is almost equally interesting. It involves the question of railroad and lake transportation and the public building question in a lesser degree than at Cleveland. The railroad accommodations, the station itself and its location, in Buffalo have of late years been for the public, very inadequate. The present plan solves the question of railroad convenience by making the station central and commodious and at the same time it opens in an ideal way the focal point of the city to the fine lake front and gives to the public buildings a dignified approach.

Mr. Day also showed illustrations of the plan of the commission appointed four years ago by Congress, for the development of the city of Washington, and showed how in spite of opposition the scheme was being followed in the placing of the recent new buildings. Drawings for the new Pennsylvania Railroad terminal were shown and in this connection the studies for the new stations in New York were also exhibited.

They seemed to be among the largest and in a way the most difficult programmes that as yet American architects have had to follow and their size and scale perhaps give one a better idea of the practical requirements of our civilization than even the great office buildings and hotels. It is interesting to see in the working out of all these great problems the interdependence of the architect and engineer.

Tantalum Lamps.

The Electrical Engineering Department has recently been testing some of the new tantalum incandescent lamps that have aroused so much attention. The lamps resemble in external appearance the ordinary 16 c. p. Edison incandescent lamps, except that they are a little broader. Internally, the filament, instead of forming a loop or a pair of loops, is run up and down in a zigzag path over a cylinder form, like the binding cord of a bass drum. The bends of the filament are loosely supported by radial steel wires which project from a central glass stem. There are eleven of these radial supporting wires, like umbrella ribs, at the top of the drum and eleven more at the bottom. The tantalum filament, strung up and down on these supports is about 65 cms. long and is 0.05 mm. in diameter, for a 110-volt-25-hefner lamp (22 horizontal British candles) consuming about 42.5 watts or 1.7 watts per hefner. The ends of the filament are fastened to steel wires, which lead outside to the lamp-base through short platinum sealing-in wires in the usual manner. The candle-power of the lamp is nearly uniform in all directions perpendicular to the axis, owing to the symmetrical disposition of the filament.

In a carbon lamp, the resistance of the filament, when hot, is only about half that when cold. But in the tantalum lamp, the resistance hot is five or six times as great as the resistance cold.

The life time of these lamps is stated by the makers in Germany to be about the same as that of the ordinary carbon lamp. If, therefore, these new tantalum lamps cost no more than carbon lamps, and consume less than 2 watts per candle instead of the present 3 or 3.5 watts per candle, with the same duration of life, we may expect metal filaments to supersede the carbon-filaments.

"The possibilities of a modern and up to date business system have recently been shown in a striking manner by the Central Elec. Co. of Chicago. With offices and warehouses completely burned out one morning, their business was before noon of the same day in full operation in new and well equipped quarters."

POWER STATION AND PENSTOCKS.

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THE PUYALLUP RIVER WATER POWER DEVELOPMENT AND HIGH TENSION TRANSMISSION TO SEATTLE AND TACOMA, WASHINGTON.*

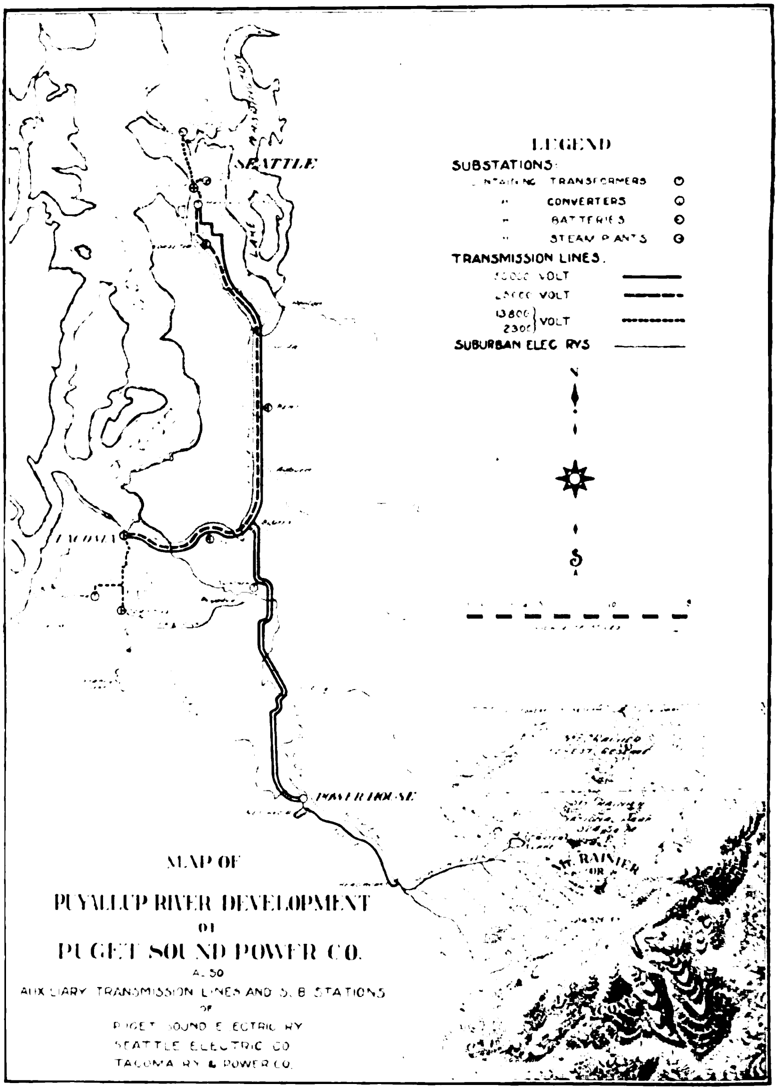
By J. F. Vaughan, '95.

(Read before the Harvard Engineering Society, Feb. 20, 1905.)

At the last meeting of the Institute of Electrical Engineers in New York, Mr. Mershon read a paper which is likely to become historic. He treated the subject in the nature of a prophecy, indicating by a mathematical discussion of the commercial problem the distance to which electric power might be economically transmitted in the future. It is interesting to study the problems and limitations of the present state of the art, and to note the simultaneous working out of the high head hydraulic problems so intimately connected with work of this kind in the West. To illustrate and to suggest material for discussion, a description of the Puyallup system recently put in operation in the State of Washington may be of interest.

To begin with, the natural conditions of this power are unusual. Examining the map, we see how the prevailing winds laden with moisture from the Japanese current off the coast, blow inland, first over rich lowlands near the coast, next through a densely wooded plateau, almost free from snow the year round, and finally striking the glacial peak of Mt. Rainier, the highest mountain in the United States (Alaska excepted), ris-

* From a lecture to the Local Section A. I. E. E.


LEGEND
SUBSTATIONS:
CONVERTERS
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POWER HOUSE
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MAP OF
PUYALLUP RIVER DEVELOPMENT
OF
PUGET SOUND POWER CO.
ALSO
AUXILIARY TRANSMISSION LINES AND SUB STATIONS
OF
PUGET SOUND ELECTRIC RY
SEATTLE ELECTRIC CO
TACOMA RY & POWER CO.

ing 14,456 feet above the sea, and covered with perpetual snow and ice. The result is, in winter, a heavy precipitation and run-off from the plateau and storage on the frozen mountain; and, in summer, a second supply to the mountain streams from the rapid melting of the mountain glaciers. The value of this summer flow to those familiar with the ordinary Western streams which run bottom up at this season, as they say, will be evident. The precipitation on the mountain is estimated at 140 in., annual.

The Puyallup River, draining five glaciers and running through the timbered plateau to the lowlands, provides a water power of the above characteristics. The rapidly growing commercial centers of Seattle and Tacoma on the coast, about 50 and 30 miles respectively from the junction of this river with the Mowich, a river of the same kind, furnish a profitable market for the power. This power the Puget Sound Power Company has developed to the extent of 20,000 h. p., making provision for an extension to double that amount.

Briefly outlining the system:—

Water is taken from the Puyallup River below its junction with the Mowich; is then carried by a flume along the canon sides to a reservoir on the tableland, and then dropped through steel pipes to the water wheels in the power station on the bank of the river deep down in the bottom of the canon. Current from generators driven by the water wheels is transmitted at 55,000 volts to Seattle and Tacoma for operating the local street railway and lighting and power systems, to the substations of the interurban third rail road between the cities, and to various towns in the neighborhood for lighting, power and miscellaneous uses.

Dam and Intake.

From the nature of the river, which, in freshet, brings down sand, boulders, and other debris, a deflecting weir, in the form of a low A-shaped timber crib faced with timber, only high enough to deflect the water into the flume without offering

DAM AND FLUME INTAKE.

obstruction to freshets, was built across the river, and cut slightly away at the crest on the flume side to maintain a scour on that side of the river. During the first freshet the river covered the up-stream with boulders, graded down-stream into smaller stone, pebbles, gravel, and finally sand near the crest, leaving a clean channel across the entrance of the flume intake. This intake is of concrete masonry 63 feet long, tapering to the flume where a radial gate operated by water counterbalance may be operated from the attendant's cottage on the hillside above.

Flume.

The flume, laid with a hydraulic grade of 7.5 feet to the mile, follows the river along the canon sides like a mountain railway. It is of timber frames 8 ft. by 8 ft. on bents heavy enough to carry the construction trains. For the present development, it is planked to a height of 5 feet only. The only peculiar features of the flume are the smoothness of the curves and the precautions taken to pass off the finer glacial and river sand which, if allowed to reach the water wheels, cuts the nozzles and buckets like a sand blast. Several devices are used, as, for instance, deep pockets built into the bottom of the flume at intervals and provided with baffles to prevent churning and blow-offs to discharge the sand; herring-bone shaped plates or knife edges called undercurrents on the bottom of the flume, the apexes pointing down stream and provided with discharge holes in the flume bottom. To provide for repairs, the flume is divided into sections by needle gates and spillways at various points, and to regulate the height of the reservoir a large spillway at the entrance to pass off surplus water.

Reservoir.

The reservoir, on the plateau, at an elevation of nearly 900 feet above the power station, is of sufficient capacity to run the plant at full load for 8 hours. The fine hardpan, or boulder clay, forming the plateau, required dynamite before a steam

RESERVOIR SHOWING FLUME AND FOREBAY.

shovel could get hold of it. The excavated material proved to be ideal fill for the embankment built on the lower side of the site, puddling to a soupy consistency, and in a few hours taking a set like natural cement.

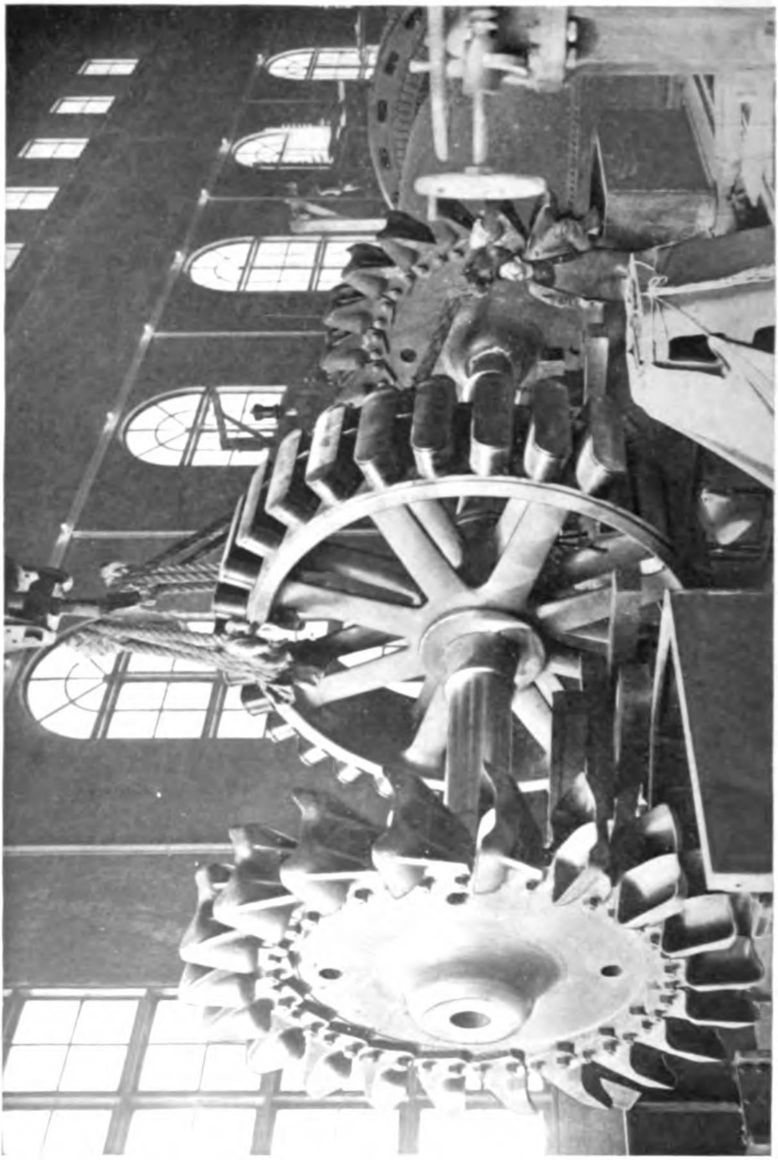
The flume enters one end of the reservoir passing to a concrete basin in front of the forebay to permit emptying and cleaning of the reservoir without interruption to the plant. The basin serves to prevent air from entering the pipes and making trouble. From this forebay, which is of concrete, provided with a gate for each pipe line, the nine pipes, one for each unit and one for two exciters, drop precipitately into the canon producing an effective head of 870 odd feet in a distance of about 1700. Although this head is less than half that of one of the California plants, one can imagine, nevertheless, the precautions necessary to handle safely such a column of water, which, in each main pipe, represents a kinetic energy of about 1,000,000 ft. lbs.

Each of the main pipes is of riveted boiler plate 4 ft. in diameter and $\frac{1}{4}$ in. thick at the upper end, and tapering to a diameter of 3 ft. and increasing to a thickness of $\frac{3}{4}$ in. at the power station. The use of relief valves was considered, but abandoned as a possible danger in case of the failure of the valves to operate properly. The weakest part of the line is the nozzle tips which would probably blow out in case of excessive water hammer. The pipe lines are anchored at intervals by massive concrete abutments designed to also drain away all surface water. For further security, the pipes are protected by backfilling of earth planted with quick-growing vegetation.

Power Station.

On a bench blasted out of the rock on the edge of the river is built the power station, the generating house of concrete, brick and steel below and the transformer and switch house adjoining and over the penstocks on the hillside.

The generating house, at present 266 feet long by 100 feet wide, contains four 3500 kw., 2300 volt, 3-phase generators of



GENERATING UNIT DURING CONSTRUCTION.

the revolving field type, each driven by a pair of Pelton water wheels of 7500 h. p. capacity, and two 150 kw., 125 volt exciters. The completed station will provide for four additional generators and a motor driven exciter. In addition, a single Pelton wheel on each exciter has direct coupled to it an induction motor connected permanently across the 2300 volt busses. The purpose of this motor is to provide a relay in case the wheel nozzle clogs or the wheel is otherwise disabled, and also acts as a regulator drawing current when the speed falls below normal, and absorbing power as a generator on overspeed.

The weight and speed of the rotating parts of the generating unit, — two overhung wheels of about 10 feet diameter, mounted one on each end of the shaft with the revolving field between, weighing about 35 tons, running at 225 r. p. m., — present an interesting mechanical problem. The two large bearings are ring oiling, fed by a motor driven centrifugal pump and gravity system, and, for starting, with oil from a force pump at sufficient pressure to lift the shaft off its seats. The bearings are also provided with circulating water and thermostat alarms on the switchboard.

Water is brought to the wheels from each penstock through two nozzles of the needle type, arranged for automatic deflection by a Lombard governor for speed control, the operation of the needles being for economic adjustment of the discharge to the load on the machine. Provision is made for automatically adjusting the needles to the load by a secondary action of the governor on an electric motor geared to the needle stems, a novel combination which promises well. Each nozzle is also provided with a motor operated gate valve. The main and exciter units are started, stopped, and controlled from the main switchboard.

The transformer and switching house, forming the up-hill half of the station, is built with the step-up transformers at the bottom opposite the generator, the low tension wiring and switches on the floor directly above, the high tension buses and switches still higher up, and above all the wire tower, from

which the transmission lines lead and containing the lightning arresters.

The scheme of electrical connections is: —

Four generators connected through oil switches to either of two sets of low tension buses; three sets of step-up transformers similarly connected to these buses on the other side. In the same way the high tension side of each bank of transformers will be connected through high tension oil switches to a duplicate set of 55,000 volt buses, each bus being connected through an oil switch to one of the transmission lines. One set of high tension buses only is in place, sectionalized by oil switches for the present, one section corresponding to each bank of transformers. Thus, we have in the completed plan a means of combining generators, transformers and lines into different groups, or of dividing the station into separate units from transmission lines through to generators. In testing a faulty line, one generator and transformer bank may be separated for the purpose, as in case of burning out short circuits or grounds. This plant, operating the greater part of the time without the aid of other sources of power on the line is necessarily more elaborate in switching apparatus than many of the other Western plants which are paralleled with one or more other plants at all times. To minimize chances of interruption from short circuits on the system, the line transformer and generator oil switches are provided with time limit relays, the time element being graded from the shortest on the lines to the longest on the generators.

Synchronizing is done on the low tension side.

The transformers are arranged in three banks of three each, connected, Δ Δ, each bank being of the capacity of two generators, thus giving 50% spare capacity in the third bank. The transformers are of the usual oil insulated water cooled type. In erecting, special care was taken in testing the oil for breakdown resistance, in drying out traces of water, and in drawing it into the cases under a vacuum of 26 in., followed by a second baking out in the transformer case before putting into service. Static dischargers in the form of shunt lightning arresters on

the low tension side are used to protect the transformers against unusual disturbances.

The fire hazard is reduced to a minimum by setting each bank of transformers in a separate concrete cell with automatic fire doors, and piping to drain off the oil into the river in an emergency. An internal explosion of oil will be resisted by the strength of the boiler plate casing of the transformer, while a fire from oil thrown out will be smothered in its own products of combustion by the closing of the fire door.

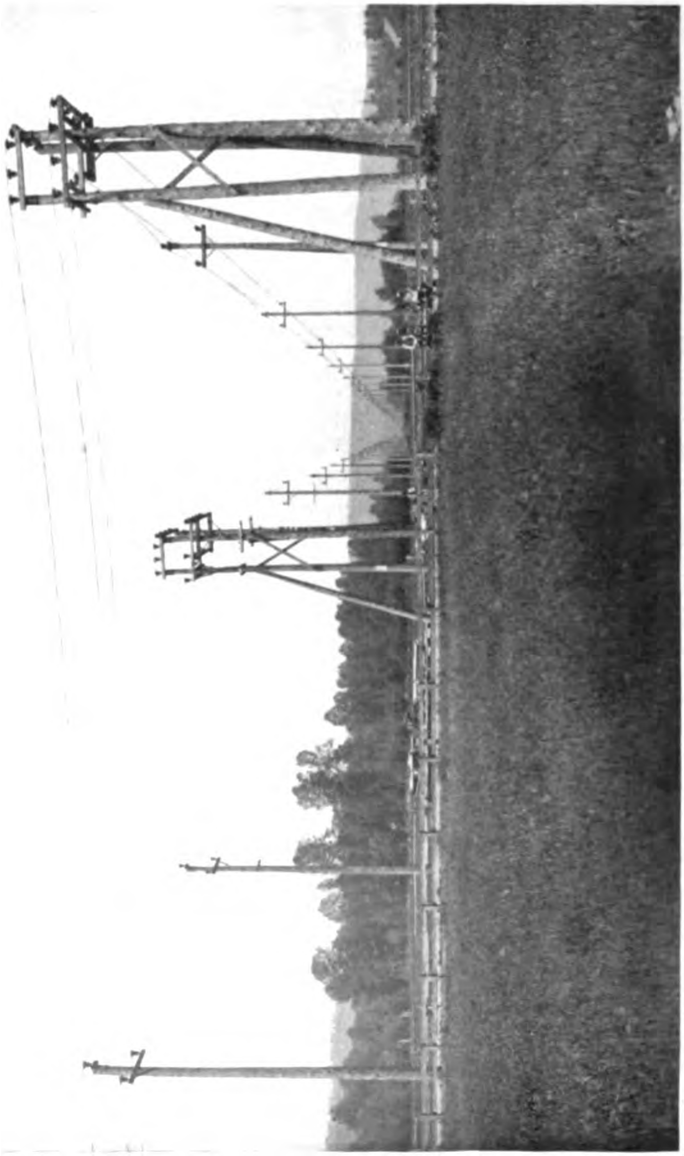
Both high and low tension wiring is largely in fireproof cell work, and all the oil switches are motor driven and operated from the main switchboard on the gallery at the end of the generating room.

The switchboard is of the remote control type arranged in the form of a crescent on the gallery of the generating room as already mentioned. This places the control of all the station apparatus, transformers, transmission lines and ultimately the head gates at the reservoir under the control of one attendant, who, in addition to his direct view of the indicating and recording instruments connected with the station apparatus and the lines, and a water level indicator connected with the reservoir, keeps in touch by telephone with the operator at the headworks, reservoir and sub-stations, and with the patrolmen on the flume and transmission lines. In addition to the usual indicating and integrating instruments the switchboard is provided with the General Electric Company's new type of curve drawing instruments, keeping a continuous record of current, voltage and station output. Similar records are kept in the principal sub-stations.

Transmission Line.

The transmission system is in duplicate throughout.

From the power house two parallel transmission lines run a distance of 22 miles to Bluffs, a station on the line of the Puget Sound Electric Railway, 9 miles from Tacoma and 25 miles from Seattle. From Bluffs one line runs for a great part paral-



RIGHT ANGLE TURN IN TRANSMISSION LINE.

lel to the transmission line of the Puget Sound Electric Railway, to Seattle, and one to Tacoma, also parallel to the transmission line of the Puget Sound Electric Railway.

The transmission line of the Puget Sound Electric Railway is at present operating at 27,000 volts; but the line is designed for operation at double this voltage, so that, when this line is changed over to a 55,000 volt basis, there will be two complete and independent pole lines from the power house to Seattle and Tacoma. At Bluffs there are erected junction pole switches, by which the two transmission lines may be cut through independently, one to Seattle and one to Tacoma, or both lines put in multiple, or any section isolated without interfering with the operation of the other sections. The wires are arranged on a 72 in. equilateral triangle, one 3-phase line per pole line.

The transmission line is necessarily the most exposed and weakest part of the system, and insulation the weakest point of the line. Hence, every effort was made to produce a rigid construction and especially a reliable insulator, and the results so far reported, — none failing from electrical or mechanical weakness,— are certainly very gratifying. The insulators are of special design, and were submitted to puncture test before shipping and again after assembling and before putting up. Sample insulators, made up to select from several designs, gave in this case under an artificial precipitation of $\frac{1}{2}$ in. per minute at an angle of 30° from the horizontal an arc-over voltage of between 90,000 and 100,000 volts, which means in operation a factor of safety of over 3. The mechanical strength tested to a wire pull of about 4,000 lbs. and the behavior of the insulator under electrostatic charge was very satisfactory.

There has been considerable trouble on the coast from burning and digesting of wooden pins exposed to salt fog. For this reason one of the lines was fitted with galvanized malleable iron throughout, and the others with eucalyptus pins waterproofed by boiling in linseed oil. The long span construction using steel windmill towers was considered, but abandoned, partly because it was new and untried, and partly on account of the excellent timber available on the ground for the ordinary con-

struction. More recent experience has brought out the advantages of this construction and appears to show on the average little difference in cost. The Puyallup lines are transposed. making a third of a turn about every four miles.

The telephone system has already been mentioned. Along the transmission line two wires of No. 10 copper are mounted on double petticoat glass insulators on a cross-arm 7 feet below the main cross-arm. The wires are transposed about every 1200 feet. To avoid accidents to the operators from static induction, — which in the case of one system has produced a difference of potential between wires and grounds of 2,000 volts,— the telephone booths are insulated from the ground. The transposition appears to take care of noise from induction from the transmission line. In order to insure reliability of service this line is supplemented by a line rented from the local telephone company.

Distribution.

In the distribution of current there is little unusual. In Seattle and Tacoma banks of pairs of 2,000 kw., transformers Scott connected, step-down the current from 50,000 volt, 3-phase, to 13,800 volt, 3-phase, or 2,300 volt, 2-phase, for local distribution, or for still further reduction and transformation to operate a. c. and d. c. lighting circuits, motor generators for railway and battery work etc. As the system grows, an effort will be made to have sufficient synchronous apparatus in service to properly control the power factor.

In closing, a few remarks on the results obtained in operation will be of interest.

With the aid of a log swung from a cable in the current of the river at the headworks, it has been found possible to keep the channel free and in its proper position. While there was some trouble from the cutting of nozzles and wheel buckets from sand brought down when the system was first started, the sand devices appear to be giving fairly good results to-day. The glacial silt which is so fine as to remain in suspension in

quiet water for many hours, is not sharp enough to more than polish the metal surface.

The loss of head in the pen-stocks, although figuring about 12 ft. when the pen-stocks are running full capacity, is reported to be slightly less. As the shortest time in which a pipe line can be wholly shut off at present is 30 minutes, the gauges show no effect of water hammer.

In regard to the transmission line. It is a satisfaction to state that there have been no electrical failures of any of the insulators due to puncture or excessive leakage. A number of insulators have been changed on account of breakage from shooting or throwing stones; also, during a forest fire before the brush was cleared away from the line right of way, several insulators were cracked by heat. Although insulators damaged by shooting or otherwise have been badly broken,— in one case, in fact, half a top being destroyed,— the lines have shown no indications of trouble. Experience with the iron and wooden pins indicates that the cracking of an insulator throughout means in dry weather practically a short circuit on the iron pin and little trouble on the wooden pin. In wet weather, naturally, there is little difference. There has been no trouble from burning or other failure of pins due to leakage. The greater strength of the iron pin gives it preference over the wooden pin.

Considerable trouble was expected in the operation of the telephone line, but although the line from the power house down is mounted directly on a cross-arm on one of the transmission pole lines and is connected to the telephone system of the Interurban Railway and through an oil insulated repeating coil to the local telephone service in Seattle,— which means that part of the line is operated under a 55,000 volt line and part under a 30,000 volt line for a time fed from a different source of power,— there is in general less disturbance in the telephones even when talking with the Seattle service than is often found on the lines of the local service itself. Tests for electrostatic induction from the transmission line indicate a difference of potential between the telephone wires and ground of not over 150 volts.

The charging current of one line from the power station to Seattle is about 900 k. v. a., and on the other line to Tacoma about 750 k. v. a., or approximately 19 k. v. a. per mile. The power factor swings about unity, above or below according to the load on the system. On the present load of the plant, amounting to a demand of between 12,000 and 13,000 kw., the daily load factor approaches 70%, which figure by the sale of wholesale power is expected to materially increase. The old steam stations in Seattle and Tacoma are operated during the extreme height of the daily peak and are held in reserve as relays in case of trouble.

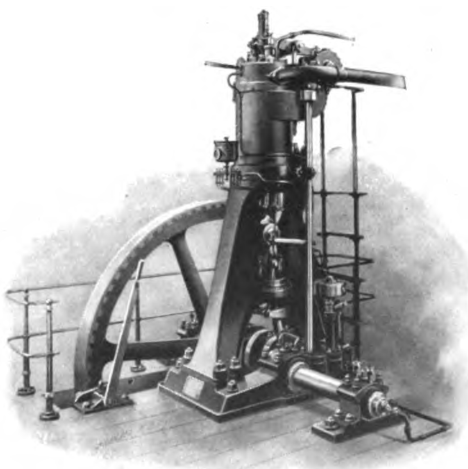
THE AMERICAN DIESEL ENGINE.

By E. D. Meier.

On June 16th, 1897, Mr. Rudolf Diesel, an eminent engineer of Munich, Germany, read a paper before the National Society of German Engineers about an internal combustion engine he had invented, which approximated in practice the ideal cycle of Carnot.

The economic efficiency of his engine was shown to be double that of the best steam engine. He invited all engineers to visit the works at Augsburg to verify his claims by rigid tests.

Engineers from all Europe, and from America responded, and came home convinced and converted. Practical difficulties were indeed predicted and encountered. But in a few years they were successfully overcome, and the engine entered the power market as the most economical of prime movers. But the claims set forth as to the economy of this device were so large



FIRST GERMAN MOTOR, 20 H. P.

and far-reaching that most practical men received them with a shrug of the shoulders. They were, nevertheless, not only true,

but somewhat under-stated. From the small Diesel motor of twenty B. H. P., which gave these remarkable results, has grown by a natural process of evolution the American Diesel Engine of to-day, at present built in sizes from 75 B. H. P. to 450 B. H. P.

A short explanation of the working of this engine may be opportune.

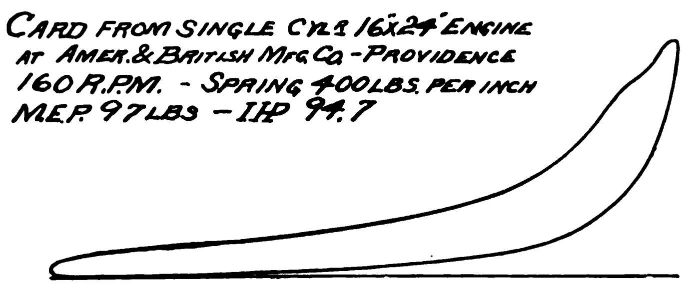
The Diesel Engine is essentially an oil engine, aud not a gas engine. Gas engines, and previous oil engines, which acted on the gas engine principle, have all in common the explosion of a charge. This charge is a mixture of a given quantity of gas, or of a given quantity of oil vaporized so as to act as a gas during the process, combined with a quantity of air varying from seven to eleven times the volume of the gas or vapor. It was well known that some previous compression would add to the economic results of the explosive action. But in all cases the power was obtained by an explosion, which, from the moment of ignition, was beyond control of the operator, or of the governing mechanism of the engine. This fact limited the efficiency of all governing devices which could be applied, and troubles with the ignitor caused other irregularities, so that, even where local conditions made the gas engine (or vaporized oil engine) the worthy competitor of the steam engine, uncertainties of its operation threw doubt on the wisdom of the substitution.

Furthermore, a cheap gas, necessitating the installation of a large and cumbersome producer plant, was the only escape from such costly fuels as gasoline or kerosene.

The Diesel makes the use of the cheapest liquid fuel, such as crude oil, fuel oil and distillates, possible. To these, recent developments have added the waste product from gas works, known as light water gas tar.

The Diesel Engine works on an entirely new principle. First, it dispenses with the so-called charge or mixture. Its cycle is the same as the gas engine, the well known Otto cycle. There its similarity with the gas engine ends absolutely; in everything else it follows the precedent of the steam engine.

Its first stroke is a suction stroke, drawing in a cylinder full of pure, clean air; on the second stroke, it compresses this to a degree and consequent temperature sufficient to ignite any fuel which may be injected into it; at the beginning of the third stroke, a small quantity of fuel oil is injected into this red-hot air as a spray by a jet of highly compressed air, and thus in a completely atomized state the fuel meets and mixes with the hot compressed air in the cylinder, burning completely, and during a period of time exactly regulated by the governing mechanism of the engine, generally through one tenth part of the stroke, subsequent to which the stroke is finished by the expansion of the burnt products; the fourth stroke discharges



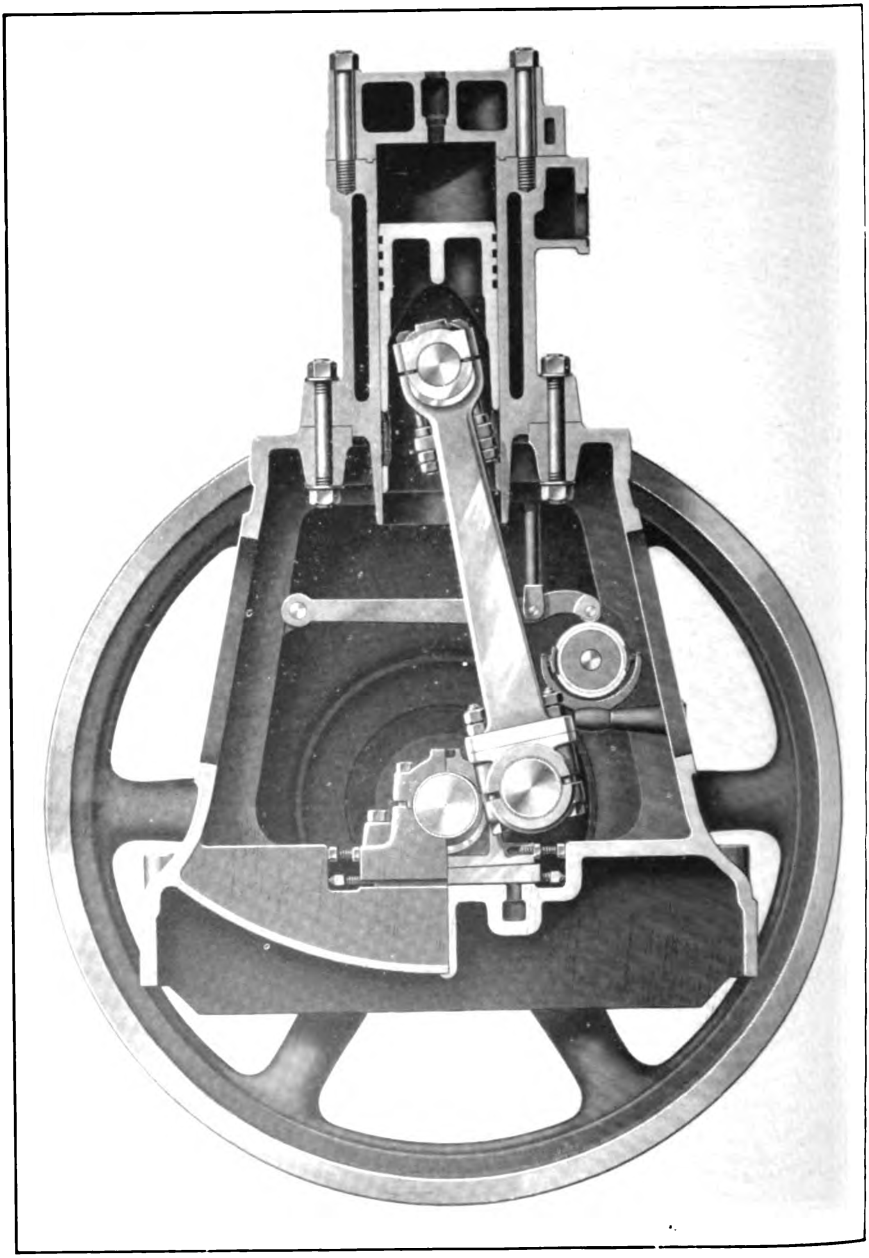
these products of combustion, and leaves the cylinder empty and ready for another suction stroke.

It is evident that the work expended in compressing the cylinder volume of pure air is given off again to the shaft of the engine during the combustion or motor stroke, so that the loss is simply the frictional loss during the compression stroke.

This simple process, absolutely new and original with Diesel, has enabled him to accomplish with one half pint of common crude or fuel oil as much as the explosive engine does with a full pint of the much more expensive gasoline.

A recent comparison of results, extending over a period of regular daily service of six weeks, has shown the consequent economy of the Diesel Engine over a first class gasoline engine, which it displaced, of 600 per cent.

The modest statements set forth some years ago by the promoters of the Diesel Engine, and covered by absolute and bind-



SECTIONAL VIEW, DIESEL ENGINE.

ing guarantees, are that 100 B. H. P. hours measured in the crank shaft of the engine will require not exceeding eight gallons of crude oil or fuel oil when the engine is running at or near its rated capacity, nor more than nine and a half when at or near half-load.

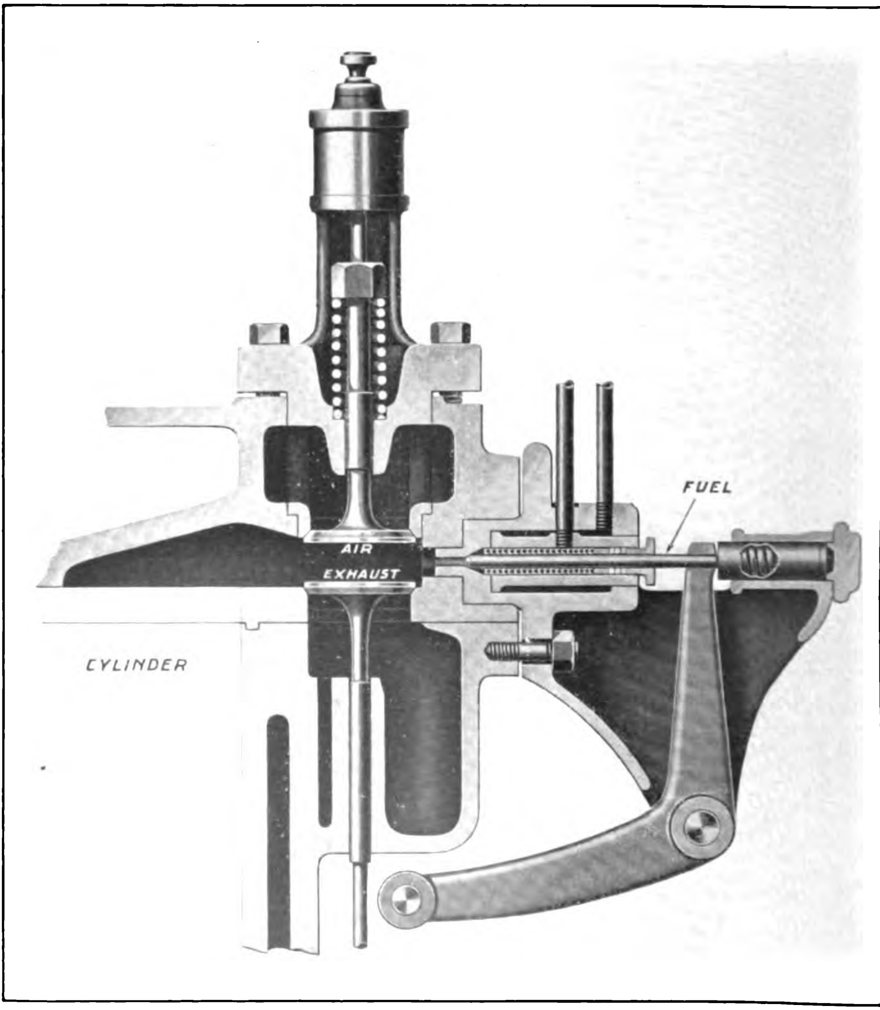
The regulation in the Diesel Engine is not dependent on hit or miss, but can be followed up or down the scale as closely as in a steam engine. In the latter it is a question of cutting off more or less from a pretty large volume of steam at each stroke; in the Diesel Engine it is the finer one of cutting off a more or less minute quantity of oil from the small volume delivered by the fuel pump at each stroke. It is accomplished by direct action of the governor on the suction valve of the fuel pump, which is held open during a greater or less portion of the pressure stroke, and thus the pump delivers the exact quantity of oil required during each motor stroke of the engine. While the mechanism is necessarily smaller, and more delicate than in the steam engine, it also requires less power, and its effect is more immediate.

In a compound steam engine the volume of steam left in the high pressure cylinder at the point of cut-off must be used in the next stroke of the low pressure cylinder, whether at the time more or less would be the proper quantity for that stroke. In the Diesel Engine the regulation acts on each cylinder just at the time and in the exact quantity then required.

There remains only the drawback common to all four cycle engines, — that there is but one motor stroke for each two revolutions. For electric light work, triple cylinder engines and heavier fly-wheels successfully overcome this, while for electric railway work resort is had to still larger fly-wheels and six cylinders by coupling two triple cylinder engines to the two ends of the same dynamo shaft.

As for the accessibility, reliability and durability of the engine, four years of experimental work has placed these fully on a par with the best steam engine practice, and since then, two years, in some cases three years, of continuous service by a number of Diesel engines of the New American type, give additional guarantees.

I have heretofore given a graphical comparison of the thermal efficiencies of a justly celebrated steam engine, that designed by Leavitt, for the Louisville Water Works, of Rankine's



ADMISSION VALVE, DIESEL ENGINE.

ideal steam engine and of the Diesel engine. It is so instructive that I repeat it here.

Rankine first proposed this ideal cycle on January 17, 1854, and Clausius described the same cycle in 1856, quite independently of Rankine. In short, the Rankine cycle takes in all the usual activities of the steam engine, but takes account only of those losses which are in their very nature inseparable from the cycle. All those vexatious and costly losses which even the best practice does not now, nor ever can, eliminate from the problem, and which may be classed under the general heads of "radiation" and "friction," are in this ideal cycle considered as non-existent.

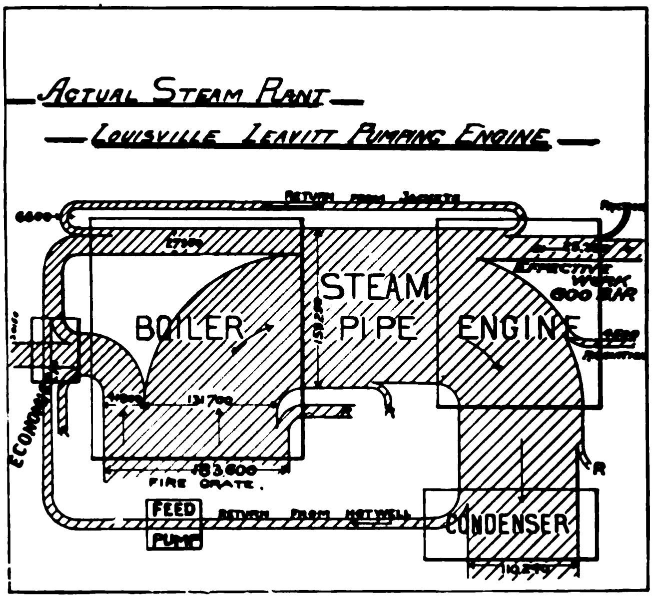
Capt. R. H. Sankey, of the British Institution of Civil Engineers, originated this method of comparison by likening the flow of heat to that of a river, with its confluents and affluents. He made his comparison from an equal output in effective work. This I have changed, for the purpose of better comparison in this case, by beginning with an equal expenditure in heat units at the beginning of the cycle, thus showing the difference in the output,— in place of in the total expenditure of heat.

In the case of the Diesel engine I start also with the same total expenditure in heat, and trace the flow of this "broad river of heat" through the entire cycle, showing the losses as actually found from a number of tests made on a 20 H. P. Diesel motor at New York. Since then larger units have shown gradual increase in efficiency.

The first diagram (p. 100) shows the reproduction of Capt. Sankey's original graphic representation of the actual results obtained during the test of the Leavitt pumping engine at Louisville.

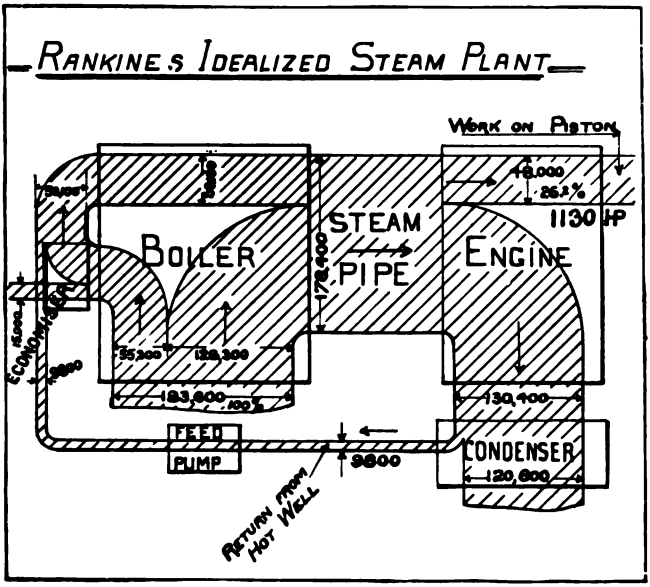
As Prof. Thurston says, "This is an exceptionally good illustration of thermo-dynamic action, and the wastes are very much smaller than are commonly observed in the operation of even good classes of steam engines." The entire river of heat, with a discharge of 183,600 heat units per minute, flows from the fire grate. To the right is seen the loss by radiation in the boiler itself. But about three fourths of the entire flow turns toward the steam pipe. Considerably over one fifth, however, flows toward the left, toward the economizer, where it loses again by radiation, but is re-inforced by a brook coming from

the hot well through the feed pump, and is further joined by a rivulet of returned heat from the jacket water, altogether forming a tributary of no mean size, joining the stream flowing into the steam pipe. Here again, at the bottom, the small rivulet escapes through radiation, but the main body passes on into the engine, where we have the smaller losses by the stream which runs into the jackets, the other which represents the mechanical friction in the engine, and the third, the radiation. By far the larger stream, however, is lost in the exhaust steam. In passing through the condenser, however, a small brook is diverted toward the feed pump to again do useful work, as above described. We have then left (in the upper right-hand



corner of the diagram) but the small fraction of 25,390 heat units, or say in effective work 600 brake horse power, which represents only 13.83 per cent. of the total which is given to the engine; or, as it is customarily expressed, this most excellent engine plant, representing the highest development of modern steam engine practice, has realized an absolute efficiency of only 13.83 per cent.

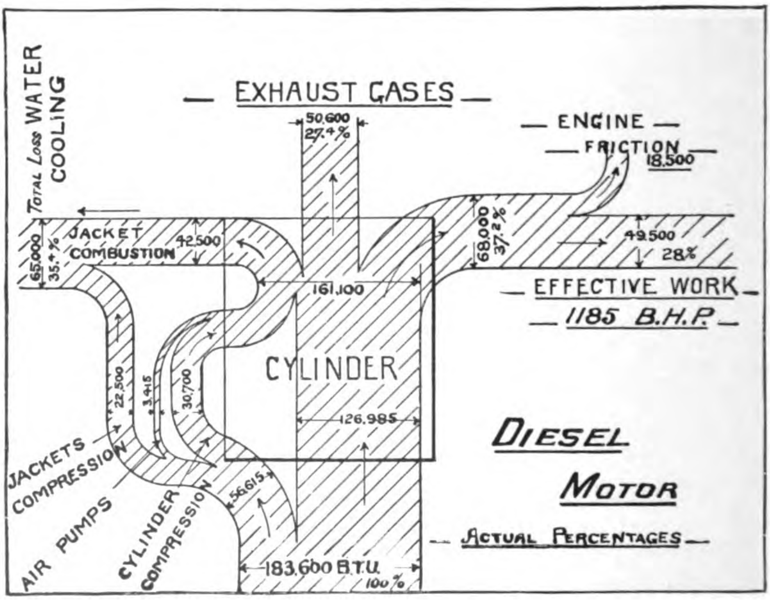
The second diagram shows the same plant running on Rankine's ideal cycle. In this friction and radiation are swept away by one happy stroke of the imagination. While a larger stream of heat is diverted to the economizer, this has become so effective that it allows only a very small current to escape toward the chimney. In fact, this represents less than eight per cent. of the original volume of flow. From the economizer



a much larger stream, augmented by the brook flowing from the hot well, re-enters the boiler, so that a total of 178,400 heat units enters the steam pipe, more than a quarter of which does useful work on the pistons. But the other three fourths finds its way, as before, to the condenser.

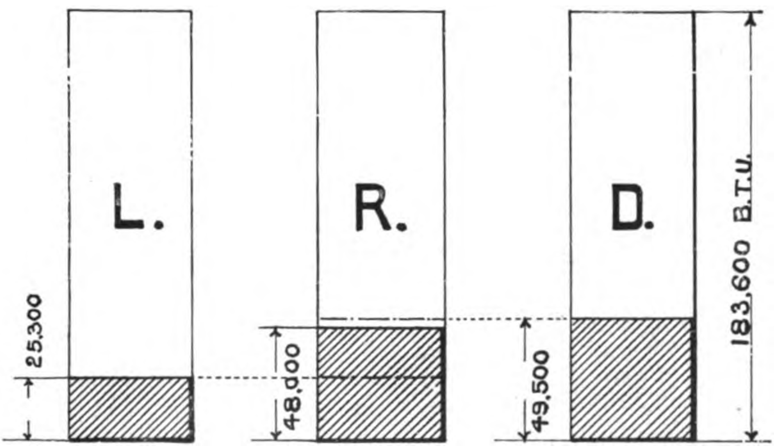
In the stream which finally turns our wheels, we find 48,000 heat units, giving us 1130 H. P., or the absolute efficiency of the Rankinized engine is 26.2 per cent. This then we may consider as the ideal possibility in steam engine practice, toward which we may strive, but which can never be reached, because we cannot dispose of radiation and friction in actual practice as easily as we have done on paper.

The third diagram shows Capt. Sankey's method applied to the Diesel motor, with the same broad river of heat, having a constant flow of 183,600 B. T. U. per minute. The bulk of this enters the cylinder on its working stroke, but we have before lost more than thirty per cent. from three causes: The one is the actual negative work done in compressing the fresh air of the charge in the main cylinder, and which represents 30,700 B. T. U. A very small stream is the heat expended in compressing air in the air pump, and a third stream aggregating



22,500 B. T. U. represents the loss by cooling, which flows into the jacket water during the period of compression. The two losses first mentioned flow back again into the cylinder during the period of combustion in the working cylinder, so that we find there a total of 161,100 B. T. U. But during combustion we lose again, as shown in the upper left-hand corner, a large stream of heat which flows into the cooling water of the jackets during this period of combustion, so that the final and total loss of heat which has flowed into this cooling water amounts to 35.4 per cent. of the total flow.

Directly upward is shown a stream of heat, amounting to 27.4 per cent. of the original flow, which we lose in the exhaust gases. To the right a good sized stream, representing 37.2 per cent, flows into indicated work. From this, however, we lose a large amount, *viz.*: 18,500 B. T. U. in engine frictions. Comparing this with the loss shown in the first diagram of the Louisville engine, this stream looks very large. In explanation, however, we must remember that the steam engine has four effective, or motor strokes, to one in the Diesel engine. As the latter has to do its whole work in this one stroke, while the frictions retard it, in all four strokes, it would be entitled to a percentage loss four times as great as that of the steam engine, without being subject to criticism as a mechanically inferior device. Furthermore, the total stream of heat on which this percentage is to be figured is more than double as large as

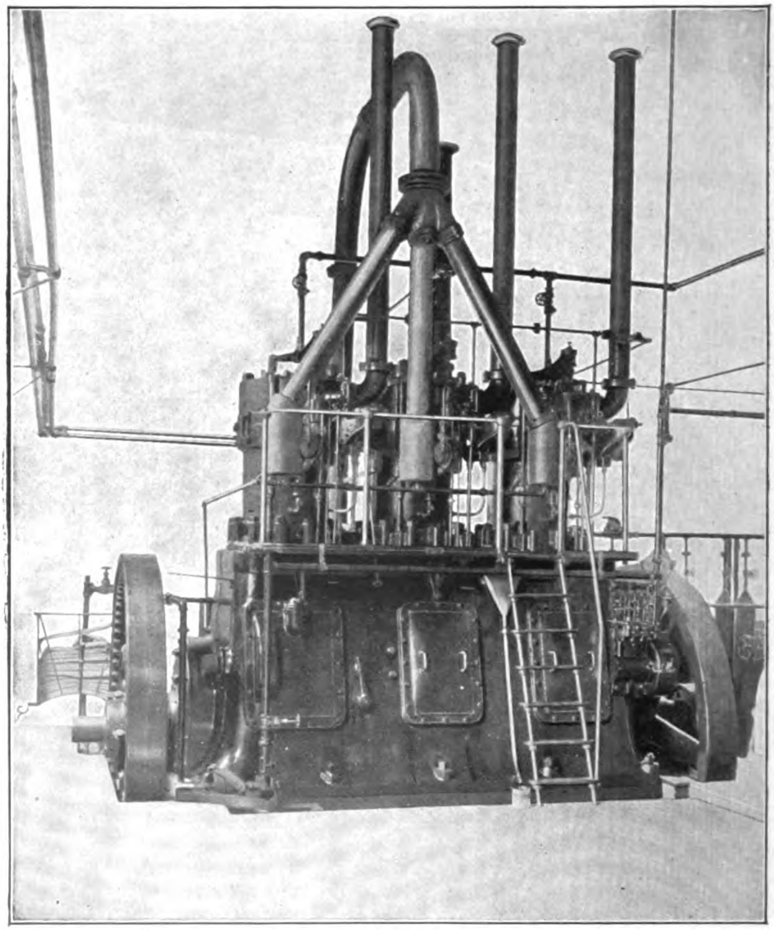


that which flows into the steam engine. If then this outflow in friction should appear eight times as large in actual quantity as that from the steam engine, it could not be considered abnormal.

Finally, we find a broad stream with a flow of 49,500 B. T. U. in the effective work of the engine, a total of 1185 H. P., or the Diesel engine has shown 28 per cent. absolute efficiency. In our larger units an absolute efficiency of 30 per

cent. is the standard performance, and is frequently excelled in actual service.

The fourth diagram shows a comparison of the three engines, by a representation of areas simply. In each case the large



225-Horse Power Triple Cylinder Diesel Engines, as installed in the Light and Power Plant of the German Tyrolean Alps at the World's Fair, St. Louis.

rectangle represents the total of 183,600 B. T. U. with which each engine is charged. The smaller shaded portions of the three rectangles show in each case the return made. The rect-

angles are marked "L" for the Leavitt engine, "R" for the Rankine cycle, and "D" for the actual cycle of the Diesel engine. This shows at a glance that the Diesel engine has in actual practice far outstripped the theoretical possibilities of the steam engine.

Turning again to the third diagram let us examine where further savings can be effected in the Diesel Engine. The engine frictions have been reduced in larger engines, and here is offered a good opportunity for the ingenuity of the designer and the skill of the manufacturer, but after all the field is a rather limited one.

The next loss that through the exhaust gases, can in many cases be very largely reduced by utilizing this heat for heating water or even producing steam for the heating of work-rooms, or for various mechanical purposes. The largest cost, that shown toward the left, as the total loss to the cooling water, can also, in many cases, be utilized for the same purposes, and it is simply a question of temperatures and quantities whether these two streams are to be separately utilized or first combined.

Acceptance tests made at Elkhart Lake, Wis., January 24–28, 1905, on a 450 H. P. direct coupled railway unit show consumption of fuel oil of

5.5 gallons per 100 brake horse power hours at full load,
6.5 " " " " " " " " over-load,
6.9 " " " " " " " " $\frac{2}{3}$-load,

A 24 hour service test at Sherman, Texas, on a 225 H. P. direct coupled electric light unit shows a consumption of Texas crude oil of 6.46 gallons per 100 brake H. P. hours at five per cent. over-load. Synchronizing tests made by Mr. W. C. Woodward, E. E., of Providence, on two direct coupled A. C. units of 120 H. P., at Mansfield, Mass., in Dec., 1904, were entirely successful.

SOME ARCHITECTURAL ELEMENTS.

THE IONIC AND CORINTHIAN ORDERS.

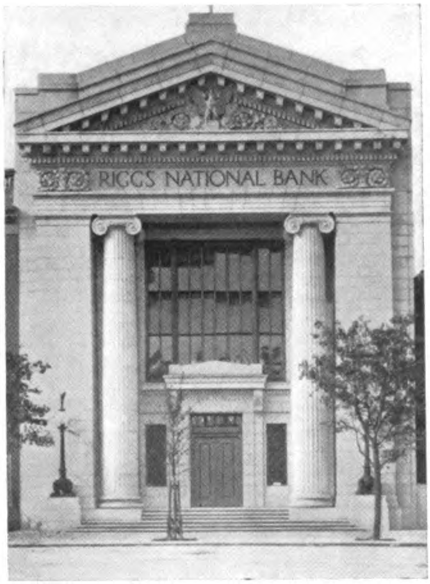
BY WALTER DANA SWAN.

THE Greek Doric Order, considered in a previous number of this magazine, is studied more for the principles of design which it involves than as an element in one's working vocabulary. It was, to be sure, modified and combined with Etruscan forms, used by the Romans, but it would more properly be considered in connection with the Roman arch order in a separate article. The Ionic and Corinthian orders, on the other hand, are used almost continually by our foremost architects and some examples are given here of their more interesting employment.

Aside from the libraries and university halls, which naturally suggest classical treatment, there is another prominent class of buildings which by their scale and requirements for monumental lintel construction seem almost to demand the employment of the orders to thoroughly express themselves. Without the order or the arch it would be very difficult, if not impossible to give the necessary scale to such structures for the banks and trust companies as those illustrated here.

The development of the "sky scraper" has brought about a reaction which is responsible for many of the interesting buildings of this type, for the banks and trust companies find that their highest financial returns lie in erecting a many storied building in connection with a much lower or single storied structure for the purposes of the bank itself, the light and air in the high building being more of an investment than the many more dark and unrentable offices. In all banks a maximum of light is essential and must be obtained either from skylight or great windows in the walls. These conditions call then for that monumental lintel treatment, the order, or as I have said, the arch, and, given the same span and height, the former cuts off less light than the latter. With regard to this point, the objection has been made

that with modern construction the heavy pier or engaged column is superfluous and cuts off required light on the sides, but if stone is used the wall piers must have the necessary thickness for stability whatever form the piers take, and what cuts off less light than a pier with a circular section? As for appropriateness of design, it seems to many of us that the order is not merely a symbol or expression of Greek or Roman life, but is a most satisfactory design for a pier. It is a scheme contributed to the art of building by the ancients and used (or abused) by



THE RIGGS NATIONAL BANK, WASHINGTON, D. C.
York and Sawyer, Architects.

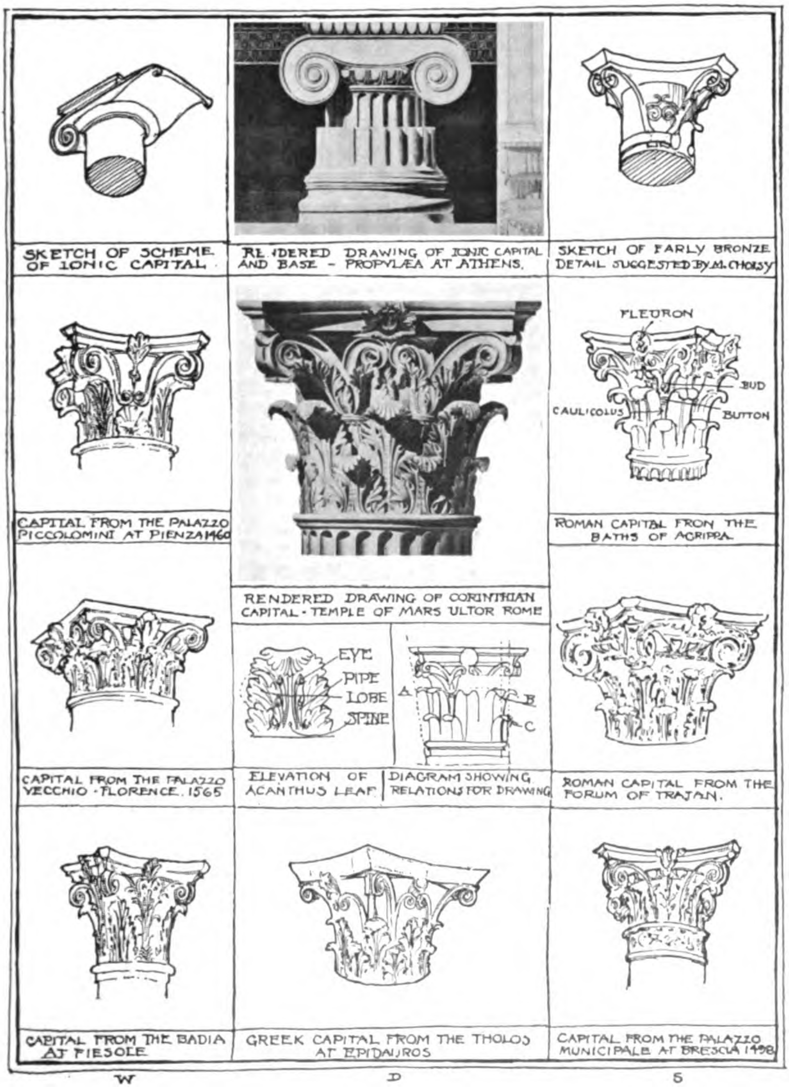
the building world ever since, according to the amount of right feeling or knowledge of principles which the designer may have had. We are beginning to see the orders in the right light. They are not the foundation of architectural design or of architectural education, but they are important details in both, and the best examples of them cannot be studied too carefully, as having beauty, dignity, and meaning, and their employment is a

suggestion of the fine continuity of the world's life. There are many conditions to be avoided in their use and some applications of them are much better than others. One does not, for instance, like to see them applied merely as decoration to the facade of a building, as has been done more than once by our best architects. This question may be open to discussion, but the persistence of the types of the order with the simple echinus, and that with the scroll beneath the rectangular abacus is, it would seem, assured and will be studied in the schools in centuries to come, certainly as long as stone and marble are used for building. In concrete and terra cotta or iron and steel we shall have, and are fast acquiring, other forms for the monumental expression of our constructive elements, and to know when and how to use each of these is to be the student's problem.

This article is concerned with the publishing of certain plates of the Greek Ionic and Roman Corinthian orders for elementary purposes, although it is felt that any attempt to confine to diagrams the life of an architectural form is usually filled with some danger to the beginner: it is also, more often than not, unjust to the form itself.

If it is borne in mind, however, that these plates are simply introductions to the systems of these orders, the diagrams may be of service to the future designer. Perhaps they will be more so if they are observed in connection with different applications of the same schemes during the centuries since their introduction to the world. Only a few of these are indicated in the sketches, and these are mostly of the Corinthian order, but they are enough to show that the proportions, the detail and the size depended on local conditions and only rarely on formulas, and then only in the most uninteresting periods of the history of the art of building.

The Ionic and Corinthian orders, while not closely resembling each other and neither being a development from the other, still have many features in common. They were both made up of elements foreign to Greece, the Ionic originating undoubtedly in Asia while the Corinthian bears witness to an Egyptian pro-



SKETCH OF SCHEME OF IONIC CAPITAL.

RENDERED DRAWING OF IONIC CAPITAL AND BASE – PROPYLÆA AT ATHENS.

SKETCH OF EARLY BRONZE DETAIL SUGGESTED BY M. CHOISY

CAPITAL FROM THE PALAZZO PICCOLOMINI AT PIENZA 1460

RENDERED DRAWING OF CORINTHIAN CAPITAL • TEMPLE OF MARS ULTOR ROME

ROMAN CAPITAL FROM THE BATHS OF AGRIPPA.

CAPITAL FROM THE PALAZZO VECCHIO • FLORENCE. 1565

ELEVATION OF ACANTHUS LEAF

DIAGRAM SHOWING RELATIONS FOR DRAWING

ROMAN CAPITAL FROM THE FORUM OF TRAJAN.

CAPITAL FROM THE BADIA AT FIESOLE

GREEK CAPITAL FROM THE THOLOS AT EPIDAUROS

CAPITAL FROM THE PALAZZO MUNICIPALE AT BRESCIA 1498

totype. These foreign ideas were adapted and refined by the Greeks and combined in their constructive schemes into forms of order and proportion. This was most characteristic of the Greek intellect, which rarely invented, but selected, developed and perfected to a wonderful degree. It is for us to apply the same spirit and find out what elements in these classic forms are to be adapted and perpetuated and what are found lacking with respect to the principles of fitness and beauty. It is now felt strongly that all art should bear the test of principled criticism, and we cannot for instance, accept and pass on as admirable, such unsatisfactory solutions of the designer's problems as the Greek Ionic corner column or the so called Asiatic Ionic base, the first of which defies the laws of balance and the latter those of unity.

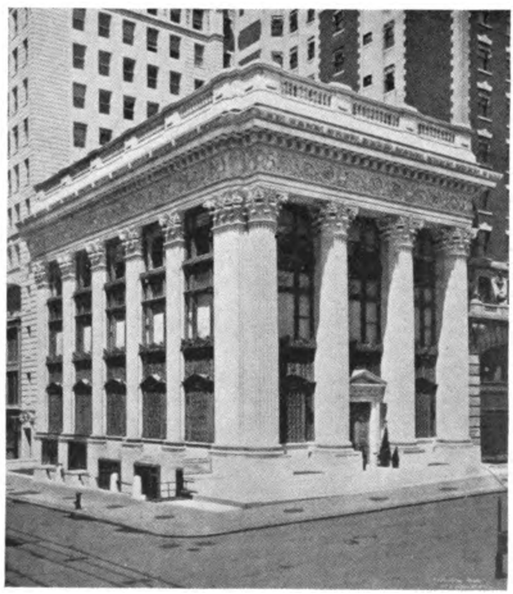
The Ionic order as given in this diagram is of the form usually distinguished as the Asiatic Ionic, for it is found like this in the Greek colonies in Asia Minor. The probable wooden origin is evident in the slender proportions of the columns, and in those members of the cornice called the dentils as well as the membered architrave. It is easy to trace the development of this order archeologically from early Asiatic structures. The Ionic order as found in Athens and its vicinity was sturdier and perhaps not so graceful, although contrasted with the Greek Doric with which it was often used at the same time, these Athenian examples have grace and refined elegance where the Doric has force and logic.

The points to be observed in this diagram of the order are that the column being slender calls for a base and the Attic base (as shown in the General Section) is better and simpler than that shown in the larger diagram. The flutes are deep and are separated by a fillet. There is an echinus supporting the square abacus, but between the two and as if receiving and resisting the pressure from above, there is a cushion-like spring, the ends of which are rolled up like the undeveloped fern frond,— apparently by their resistance to the weight on the center of the mass. The fine feature about this capital is the life in this cushion and its ends or volutes and there is no reason why we

should go on accepting poor substitutes for that living spring-like dip to the bottom of the cushion which is indicated here, but is lacking in many of the later Greek and Roman examples to say nothing of those of modern times.

The placing of the ornament in this order is considered by most of the best designers to be a most valuable object lesson in the principles of decorative design. This ornament was and is most appropriately carved instead of painted as in the Greek Doric.

Two modern applications of the Ionic order are shown. Its



THE KNICKERBOCKER TRUST COMPANY, NEW YORK CITY.
McKim, Mead & White, Architects.

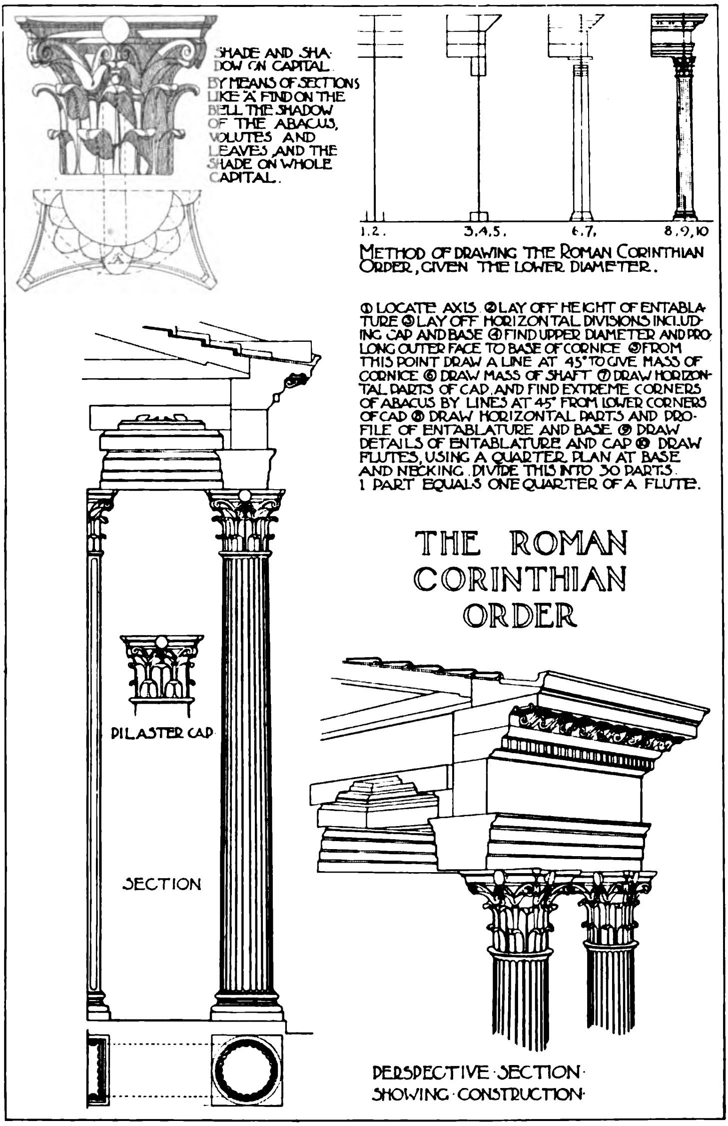
use by Messrs. Shepley, Rutan and Coolidge at Conway is a purer one theoretically than that of Messrs. York and Sawyer at Washington — both in the form of the capital and the method of construction; but practically the larger scale of the latter demands the arch (the flat or keyed arch in this case) and the height of the entablature allows the voussoirs to be of the proper

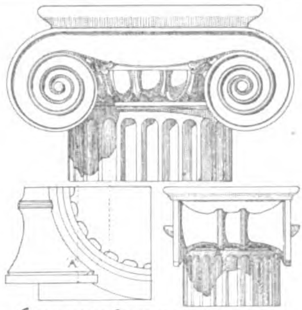
depth. Both of these modern examples are interesting as showing how the Ionic capitals were first and best used by the Greeks, between antae, or the side walls brought forward, the face of the volutes being parallel with the direction of the architrave. This direction of the main mass of the capital gives unity and meaning to the design and it was lost when the attempt was made by the Greeks to use this motive on a corner column. This problem was, to be sure, solved later by the Romans with the same general scheme of capital by making

ENTRANCE PORTICO, THE FIELD MEMORIAL LIBRARY, CONWAY MASS.
Shepley, Rutan and Coolidge, Architects.

volutes on all four corners, but the purity of the detail suffered.

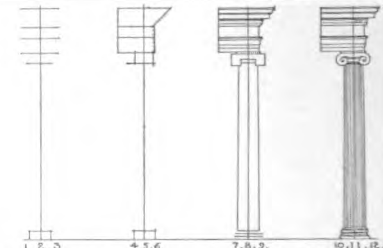
The Corinthian order on the other hand, as we recognize it to-day, and as used for instance by the Knickerbocker Trust Co., is largely due to the Romans to whose characteristics as a people it appealed more strongly than the more subtle Ionic, and although perhaps the most beautiful Corinthian capital in exist-


SHADE AND SHADOW ON CAPITAL.
BY MEANS OF SECTIONS LIKE "A" FIND ON THE BELL THE SHADOW OF THE ABACUS, VOLUTES AND LEAVES, AND THE SHADE ON WHOLE CAPITAL.
1.2.
3.4.5.
6.7.
8.9.10
METHOD OF DRAWING THE ROMAN CORINTHIAN ORDER, GIVEN THE LOWER DIAMETER.
① LOCATE AXIS. ② LAY OFF HEIGHT OF ENTABLATURE ③ LAY OFF HORIZONTAL DIVISIONS INCLUDING CAP AND BASE ④ FIND UPPER DIAMETER AND PROLONG OUTER FACE TO BASE OF CORNICE ⑤ FROM THIS POINT DRAW A LINE AT 45° TO GIVE MASS OF CORNICE ⑥ DRAW MASS OF SHAFT ⑦ DRAW HORIZONTAL PARTS OF CAP, AND FIND EXTREME CORNERS OF ABACUS BY LINES AT 45° FROM LOWER CORNERS OF CAP ⑧ DRAW HORIZONTAL PARTS AND PROFILE OF ENTABLATURE AND BASE ⑨ DRAW DETAILS OF ENTABLATURE AND CAP ⑩ DRAW FLUTES, USING A QUARTER PLAN AT BASE AND NECKING. DIVIDE THIS INTO 30 PARTS. 1 PART EQUALS ONE QUARTER OF A FLUTE.
THE ROMAN CORINTHIAN ORDER
PILASTER CAP
SECTION
PERSPECTIVE · SECTION · SHOWING · CONSTRUCTION ·



SHADE AND SHADOW ON CAPITAL

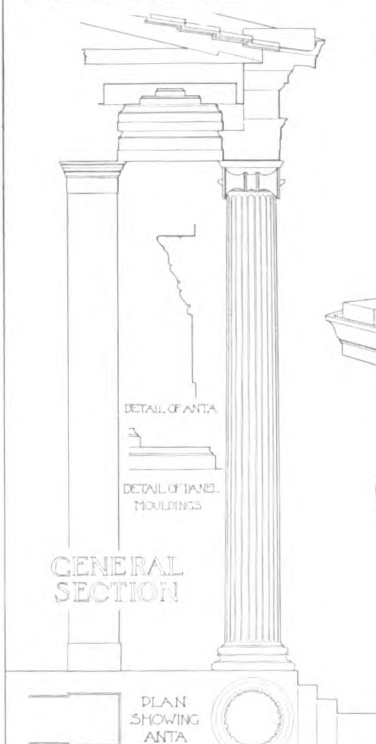
BY MEANS OF SECTIONS LIKE "A" FIND ON THE SHAFT THE SHADOW: ① OF THE VOLUTE, ② OF THE SHADE LINE OF THE BALUSTER SIDE, ③ SHADE ON ECHINUS AND SHADE AND SHADOW OF ASTRAGAL AND FLUTES.



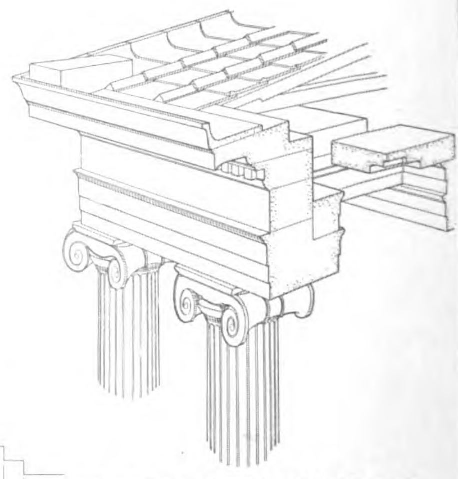
METHOD OF DRAWING THE GREEK IONIC ORDER ASIATIC FORM, WITH ATTIC BASE, GIVEN LOWER DIAMETER

① LOCATE AXIS. ② LAY OFF HEIGHT OF ENTABLATURE. ③ LAY OFF HORIZONTAL DIVISIONS INCLUDING CAP AND BASE. ④ LAY OFF FACE OF EPISTYLE AND FRIEZE. ⑤ FIND UPPER DIAMETER, AND PROLONG OUTER FACE UNTIL IT STRIKES BASE OF CORNICE. ⑥ FROM THIS POINT DRAW A LINE AT 45° TO GIVE MASS OF CORNICE. ⑦ DRAW HORIZONTAL PARTS AND PROFILE OF CORNICE. ⑧ DRAW MASS OF VOLUTES. ⑨ DRAW PARTS OF EPISTYLE, CAP AND BASE. ⑩ DRAW VOLUTES. ⑪ DRAW DETAILS. ⑫ DRAW FLUTES, USING A QUARTER PLAN AT BASE AND NECKING. DIVIDE THIS INTO 30 PARTS: 1 PART = ¼ OF A FLUTE

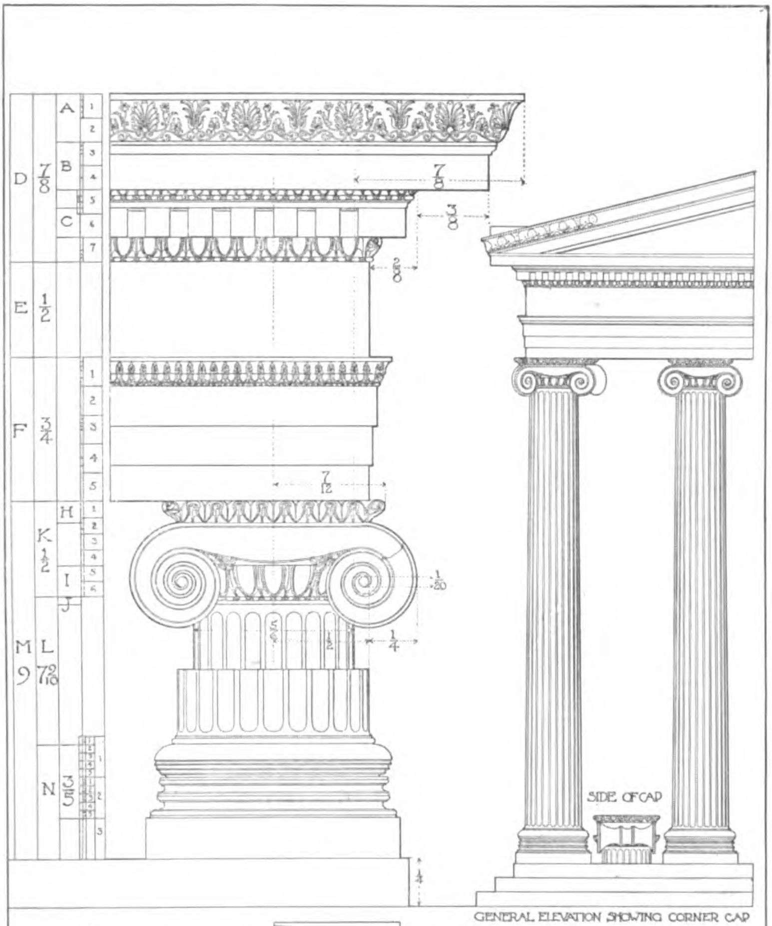
THE ASIATIC IONIC ORDER



GENERAL SECTION

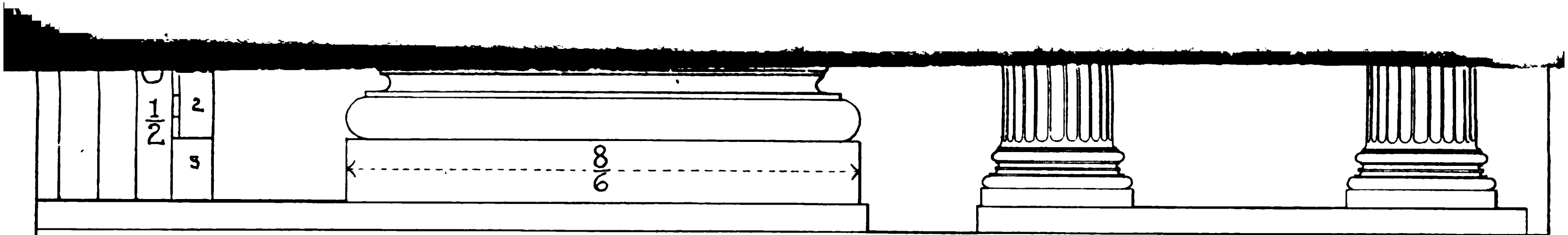


PERSPECTIVE SECTION
SHOWING CONSTRUCTION

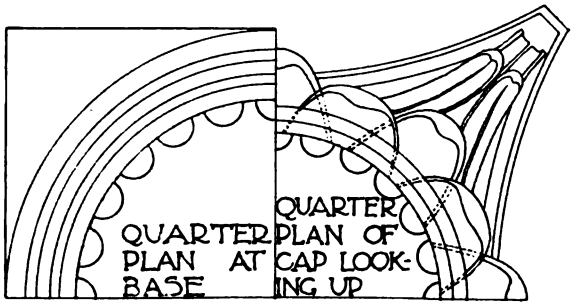


THE ASIATIC IONIC ORDER

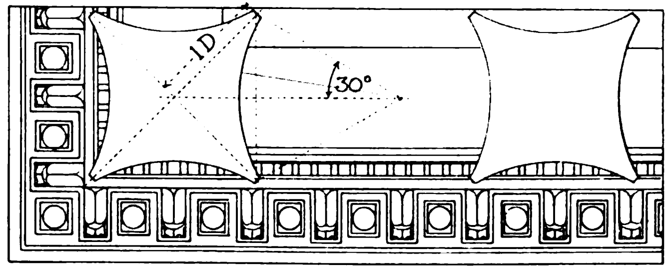
A	CYMATIUM	H	ABACUS
B	CORONA	I	ECHINUS
C	DENTILS	J	ASTRAGAL
D	CORNICE	K	CAPITAL
E	FRIEZE	L	SHAFT
F	ARCHITRAVE	M	COLUMN
G	FILLET	N	BASE



A ENTABLATURE
B CYMATIUM
C MODILLIONS
D DENTILS
E CORNICE
F FRIEZE
G ARCHITRAVE
H ABACUS
I LIP OF BELL
J VOLUTE
K CAPITAL



L ASTRAGAL
M SHAFT
N COLUMN
O BASE



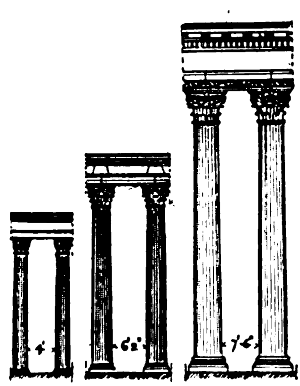
PLAN OF SOFFIT OF CORNICE

ROMAN CORINTHIAN ORDER

ence is Greek, that of the Tholos of Epidaurus, the developed type used at a large scale and appropriate to Roman civilization, and to ours in many of its aspects, was the work of the Romans of the Empire.

The Greeks treated this order usually as a slight and delicate decorative form as in the Choragic Monument of Lysicrates at Athens, or made the column a single ornamental feature as in the Temple of Apollo at Bassæ, but the Romans used it at a large scale in both exteriors and interiors, in temples, palaces and baths, sometimes most logically and again with more feeling for display than for architectural truth.

On the whole, however, its Roman career was most profitable to its development as a logical architectural element, for the mass of the volute was strengthened, giving more the appearance of support for the abacus and the arrangement of the two rows of leaves simplified into a scheme which the intelligence easily comprehends. Then the capital in detail was made to suggest a treatment of stone and marble rather than one which recalled its metal origin as the delicate, almost wiry carving of the Greeks often did. The earlier forms of the Roman Corin-



TEMPLE OF VESTA AT TIVOLI — TEMPLE OF MINERVA AT ASSISI — TEMPLE OF JUPITER STATOR AT ROME

thian capital were sturdier than the later ones, both on account of the influence of the material which in the case of the Temple of Vesta at Tivoli was of a soft stone, and of the good

feeling for scale which led the designer to keep the masses simple. Contrast for instance the capital of the Temple of Vesta at Tivoli with that of the much larger order of the Temple of Jupiter Stator, which was of marble.

This question of scale is a most important one with regard to the use of the orders and the accompanying diagrams on page 113 prepared by M. Gaudet will show how such questions as that of the intercolumnation and the amount of detail depended upon constructive conditions and not upon formulas.

The Roman Corinthian order as given in the accompanying line diagram suffers from its restriction to definite numerical relations but, it serves to explain in plan and elevation the system. A good description taken from a current text book is as follows:

*"The Corinthian capital is in form similar to a cylindrical vase covered by an abacus with hollowed sides and with corners cut at an angle of forty-five degrees, in plan with the sides of the square containing the abacus. Against this vase or 'bell' are placed two rows of leaves whose heads are curved. The first row which is applied directly above the astragal of the shaft, is composed of eight leaves; these are called the small leaves. From the intervals between these small leaves arise the stems of the second row of leaves which are larger. Between these large leaves and just over the centers of the small ones, eight stems arise, from which develop eight other leaves, which divided into two parts, recurve above the large leaves at the corners of the abacus and at the center of each of its faces.

"These leaves, which are very much distorted, are called caulicoli. From these caulicoli arise sixteen volutes of which eight large ones unroll in pairs, back to back, under the corners of the abacus, and eight small ones, also in pairs, extend towards the centers of the four sides of the abacus. Above the small volutes and against the mouldings of the abacus is a rosette. The small leaf is placed on a vertical axis against the base in such a manner that the base rests on the astragal and its face corresponds to the face of the shaft."

* Bourne and Brown "The Roman Orders."

The Roman Corinthian Entablature differs from the Ionic chiefly in the details of the cornice. In addition to the dentils in the latter there are the larger consoles or supporting brackets under the corona. These vary in the different examples of the orders from the plain rectangular masses, to the modeled forms shown in the diagram. The points which seem essential in the design of this order are that the fine continuity of the line of the shaft through the profile of the capital shall be kept, and that the mass of the volutes shall always be heavy enough.

In drawing the form it is, as one can see, very essential to have the plan, for the correct positions of the details of the leaves, as well as a proper conception of the system of the acanthus leaf, with the relative importance of the mass first followed by the spine, the eyes, the pipes, the lobes and lastly the leaves. Then it is to be remembered that in drawing the capital at a small scale the vertical elements are to be emphasized or the cap loses its character of support.

The sketch diagram indicates one or two convenient relations which help one to draw the elevation of the capital at a small scale. The line drawn tangent to the astragal from the end of the echinus is tangent also to the upper leaf at A. The lower diameter projected up gives the point of the lower leaf C and the upper diameter has the same relation to the leaf B.

TRAIN RESISTANCE IN RELATION TO THE TRACK.

By P. H. Dudley, C. E., Ph. D.

The construction of an efficient track to reduce the resistance of the passenger, mail, express and freight trains, is one of the important objects in building a railroad. The theory of the location of a line in reference to gradients and curvature, as elements of train resistance, has received extensive discussion. The theory of causing the centers of gravity of all the wheels and of the bodies of the locomotives and cars to move over the track with the least possible undulations, to reduce train resistance, has not incited academic discussion, though practically it has been given great attention. It is the problem on which I have been engaged the past three decades, and by the introduction of stiffer rails have reduced the undulations in the track, from 6 to 8 ft. per mile, to 2 ft., on 100 lb. rails, as measured by my Track Indicator.

The railroad companies in the United States for 1903 expended $126,000,000 for labor to surface and keep the tracks in order, and reduce the train resistance, and this is likely to increase per year.

Tests have been made upon the resistance of single cars and short trains, at slow speeds, from the inception of the railroads. The results were of technic value for comparison with those of other systems of transportation which they were to replace, and excel in capacity and speed. Those tests for present service are of more historic interest than practical application, as the condition of the track, on the 15 ft. or shorter rails, was inferior to the present smoother tracks, and the resistance two and three times greater per ton than upon the larger cars and trains now in service.

The resistance of the short loaded cars in England in 1830 was found to be 10 lbs. per ton of 2240 lbs. for speeds of five to ten miles per hour. The same cars empty ranged from 11

to 12 lbs. per ton. The wheels were 3 ft. in diameter, and the journals 1.75 inches in diameter by 3.5 inches in length.

Improvements in the construction of the cars and the substitution of brass for the journal bearings, reduced the resistance, to a slight extent.

Chev. F. M. G. De Pambour, in 1834, when making tests upon the English locomotives and trains of the Liverpool & Manchester Railroad, at five to ten miles per hour, found that the resistance was about 9 pounds per ton, in trains of five or six loaded coal wagons, while for single cars it was from 11 to 12 lbs. Each car loaded weighed five to six tons. His book on "Locomotive Engines upon Railways" is and will remain a classic upon the Theory of the Locomotive.

Mr. Johnathan Knight, Chief Engineer of the Baltimore & Ohio Railroad, made some experiments upon the resistance of single four-wheel cars, and found that by coning the wheel treads, he could reduce their resistance on the curves he was obliged to adopt for the line.

The flexible four-wheel truck was invented, and one placed under each end to support the car body as in present service. This was an adaptation of the rolling stock to the track of far reaching importance to American railroads, which were being built to develop the ample resources of an extensive country.

The tracks at the inception of the railroads in England were constructed upon the theory of an inelastic roadbed, with rigid foundations as for buildings with static loads.

Stone blocks with foundations were provided, upon which the rails or stringers rested, to carry dynamic rolling loads. It was expected that these would prove permanent constructions of great durability, instead of failing after a short service. The stone blocks and foundations were copied at first in this country, by the Baltimore & Ohio, the Mohawk & Hudson, the Boston & Lowell and many other railroads, but were abandoned for cross-ties on ballast. The four-wheel engines, either imported or constructed in this country, at even ten and fifteen miles per hour, rode with decided undulations over the tracks.

The Mohawk & Hudson Railroad, from Albany to Schnec-

tady, was chartered in 1826. Construction commenced in 1830, and the road opened in 1831. There was one inclined plane at Albany, and one at Schenectady, the locomotives traversing only the nearly level plateau between the heads of the inclines. It had a strap iron rail 2.5 inches by $\frac{9}{16}$ of an inch thick, spiked centrally upon pine stringers 6 by 6 inches, resting upon stone blocks of 3 ft. centers, which were set upon broken stone foundations in the road bed.

Mr. John Bloomfield Jervis, the Chief Engineer, had the "De Witt Clinton" constructed by the West Point Foundry, for one of his locomotives, and one constructed by Robert Stephenson & Company, Newcastle-on-Tyne, England, and named the "John Bull." The "De Witt Clinton" weighed 6,758.5 pounds, the "John Bull" 12,742 pounds, of which 8,745 pounds was upon the single pair of driving wheels. Both had four wheels and a wheel base of 4.5 feet, though in the case of the "De Witt Clinton" both pairs were driving wheels.

The strap iron rail formed the bearing or sustaining surface for the wheel contacts, and guide for the passing locomotives and cars. The stringer supplied the strength as a girder. The weight of the "John Bull" was too heavy for this superstructure, and was not distributed by a wheel base sufficient in length to ride steadily over the track, and was seldom used, as first received.

Mr. Jervis prepared designs for a new engine with his "leading and guiding four-wheel truck," which was constructed at West Point Foundry in 1832, and called the "Experiment." This demonstrated the value of the principle of distributed loads of the engine.

Mr. Jervis sent similar designs to Robert Stephenson & Company, Newcastle-on-Tyne, and a locomotive was constructed, called the "Davy Crocket," received and ran on the Saratoga & Schenectady Railroad in 1833.

Mr. Jervis was also Chief Engineer of this railroad. He constructed three miles only with stone blocks, substituting cross-ties and ballast, adapting the flexible superstructure to

the elastic subgrade. A four-wheel truck was substituted for the front pair of wheels in the "John Bull," which then rendered service on the Mohawk & Hudson for many years.

Mathias W. Baldwin, the founder of the Baldwin Locomotive Works, visited the Mohawk & Hudson Railroad, and adopted and used the Jervis truck for the construction of his second locomotive, the "E. L. Miller," in 1834.

Henry R. Campbell's American or eight-wheel engine followed in 1836, which now had sufficient lateral and vertical flexibility, with the necessary weight for adhesion, to run over the mountain divides superseding inclined planes.

On the Mohawk & Hudson Railroad was the inception and installation of the American theory and practice of subdividing the total load of the engine, and utilizing a portion of the weight by a forward "leading and guiding truck" to take up the looseness of the track, stiffen and strengthen the portion of the rail occupied by the heavier loads of the driving wheels. The general depression of the rail started by the forward truck wheels is continued under the driving wheels in part by the drawbar-pull, to the rear portion of the rail held down by the following wheels of the tender. With this principle of distributing the loads of the locomotive, the constraining of the stiff line section in the general depression is so efficient that the greater weights carried upon the driving wheels do not produce a proportional increase of stress, even with the expenditure of their tractive effort to the load carried upon the truck. The rail instead of forming a deep depression under the driving wheels, is retained in a more level and uniform surface in the general depression than would be the case without the assistance of the weight upon the forward truck.

Utilizing the favorable mechanical principles between the running engines and stiff rails, by causing a part of the load to stiffen and strengthen the permanent way, is unique in Mechanics, and has rendered possible the unexpected development of the railroads in the past two decades. Extending the same principle of subdivision of the load to larger types of locomotives having more than two pairs of driving wheels, the effect

of the distribution of the increased load of the locomotives upon the stiff rails has been rendered exceedingly advantageous.

The load of the locomotive produces on the track a distinct general depression, with specific deflections under its wheels. This is illustrated in Figure 1, by a locomotive on a section of track.

The trackman's surface of the rail, represented by the broken line, is in its normal position only when unloaded. It is depressed by the moving loads of the locomotive and cars to its lower loaded surface in the general depression for the necessary

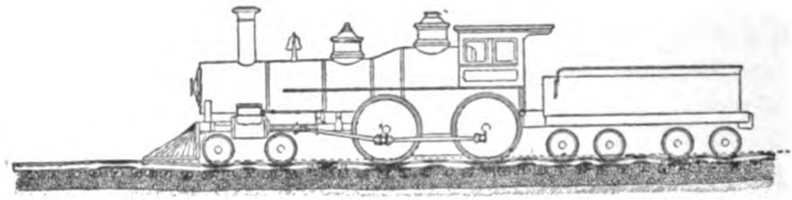


FIG. 1. The vertical scale of the "general depression" is enlarged 24 times over that for the length of the locomotive.

Fig. 1 illustrates the general depression of the rails, cross-ties, ballast and subgrade from the "trackman's surface" under moving locomotives.

The rail section from its mechanical properties as an engineering structure in distributing the wheel effects, resolves them into positive bending moments under the wheels and the constraining negative bending moments in the wheel spacing.

conjoint support of the subgrade to carry the loads which are transmitted and distributed only through the wheel contacts and produce specific unit fiber strains under them in the rails.

Examination of the tracks in England, Belgium, France or America, discloses that the superstructure of the permanent way is restricted in depth and weight, and from its flexibility and elasticity when unloaded, is a floating mechanism held in surface or not by the ballast resting on the compressible subgrade.

The rails and cross-ties are depressed by the wheel loads in the ballast from one-eighth to three-eighths of an inch under the present heavy locomotives and cars. The compression of the ballast and subgrade forms one-fifth to one-third

of the total amount of the temporary subsidence of the rail. The subgrade is affected to a depth of twelve to twenty feet, according to its material, construction and stability. There is a characteristic general depression of the rails, cross-ties, ballast and subgrade produced by each type of locomotive or car to carry and distribute the loads with specific deflections in the rails under the wheel contacts.

The reduction in train resistance from the inception of the American railroads to date is due to two important factors:

First. The improvement of the track.

Second. The adaptation of the equipment to the permanent way.

Robert L. Stevens, President and Chief Engineer of the Camden and Amboy Transportation Co., designed the prototype of the present Tee rail sections, in 1830, of about 40 lbs. per yard, height 3.5 inches, base of equal width, and the head about $2\frac{1}{8}$ inches wide. It was laid in the track in 1832, in 16 ft. lengths, and spiked directly to the cross-ties. Upon the light short iron rails, the resistance did not reduce much under 8 lbs. per ton, for freight trains, and was more for passenger trains. The weight of the section was increased per yard, though made more pear shaped for the head and web than in the Stevens section. The engines were enlarged, and the sections augmented in weight and height, which caused the iron rails to crush and exfoliate in the bearing surface. This was attributed to the quality of the iron, while the real cause, passed unnoticed, of the greater duty imposed upon the bearing surface of the rails by the larger bending moments, to make stiffer and smoother tracks. Many of the railroad companies returned to the use of more limber iron rail sections, which increased the train resistance. This was an embargo upon the development of the locomotives, cars and trains, while the cost of maintenance was excessive. Steel capped rails were tried, but soon failed.

Bessemer's invention of the pneumatic process for making steel furnished a product which in the early rails of 1865 to 1875 rendered excellent service in the bearing surface. One

steel rail would outlast ten to fifteen iron rails, and enabled the railroads to establish higher standards of maintenance of way, which reduced the cost of operating, but only to a slight extent the train resistance.

The stiffness of the rails was even less than some of the iron rail sections, and the locomotives were not enlarged.

Experiments upon train resistance were made in England, from which D. K. Clark advanced a formula having a factor which increased as the square of the speed. Reduced to American tons of 2000 lbs. it is $R = 7.2 + 0.053\ V^2$. R being the resistance in pounds per ton (2000 lbs.) and V the speed in miles per hour. This was accepted by Civil Engineers of the United States, from about 1865 to 1875, as approximately correct.

As chief engineer of the Valley Railway Company of Ohio, 1872 to 1875, I concluded from observations that this was an over estimate for American trains and track. I wished to run freight trains of 1200 tons gross weight, and the formula indicated it would be beyond the capacity of the existing locomotives. In 1873–4 I constructed my dynagraph, and found that while the formula was high for freight trains, it was excessive for passenger trains of 200 to 250 tons.

Mr. C. O. Mailloux in his article on Train Resistance in the April, 1905, number of the JOURNAL, has stated several of the important features of my investigations, so that it will be necessary only for me to refer to the prominent results.

Tests which I made on Train Resistance on the Lake Shore & Michigan Southern Railway, in the winter of 1875–6, indicated that less fuel was consumed at speeds of 18 to 20 miles per hour, on stock trains, than the slower running trains of 12 to 16 miles per hour. For ordinary freight trains 16 miles per hour was the maximum speed allowed at that time, but was soon increased. The train resistance ranged from 7 to 8 lbs. per ton.

Tests upon different roads indicated that upon new rail, well surfaced, the train resistance was less than upon the older rails with low joints, other conditions being similar. This was

observed in several tests upon the Boston & Albany Railroad in 1876–7, and was one of the most important practical results obtained, for with better track the resistance was reduced for every wheel which passed over it, by checking large generated destructive dynamic forces. I made a test in 1878 upon the New York Central & Hudson River Railroad, from Buffalo to Albany, of a passenger train of nine cars of 300 tons weight, in which the average resistance at 50 to 52 miles an hour, was from 11.5 to 12 lbs. per ton, about two thirds of that estimated by the Clark formula.

In descending the Batavia grade the speed attained was 60 miles per hour, but on the levels the maximum was from 51 to 52, the full steaming capacity of the boiler of the engine.

These tests showed conclusively that to increase the speed of the train it would be necessary to quicken the steam generating capacity of the boiler, and make the track smoother. The rails were laid with opposite joints. Such facts having been ascertained, the next investigation was the condition of the track, which was undertaken by the complete apparatus I designed for my Track Indicator. The diagrams of the undulations of the rails, under the load of 19 tons on the special six-wheel truck, indicated that the rails in all tracks had common forms of permanent set, of such magnitude labor alone could not correct them.

The light and limber rails had only small constraining negative moments in the wheel spacing, the major portion of each wheel effect being delivered to the cross-ties as they were passed. The generated dynamic shocks were so great they indicated on the dynamometrical curve at each joint. Every wheel beside overcoming the "fictitious grade" was delivering dynamic shocks of more or less magnitude, to the permanent way.

Stiffer rails were required to distribute more of the wheel effects in the wheel spacing and relieve each cross-tie of as great percentage of each wheel load as was permitted by the limber rails.

I designed in 1883 the pioneer five inch 80 lb. steel rail for the

New York Central & Hudson River Railroad, which was rolled and laid in the Harlem Line in July, 1884. It replaced the 4.5 inch 65 lb. rail and with only 15 lbs. or 23 per cent. more metal was 60 per cent. stiffer, and 40 per cent. stronger with a broader head for greater combined stability between the speeding locomotives, cars and the permanent way, than the 65 lb. rail.

The service tests of the rail were awaited with interest by railroad officials, the results in smoothness and stability of track exceeding their expectations.

The heaviest axle load under engines was 31,750 lbs. or 63,500 lbs. for the two pairs of driving wheels, and was limited to 27 locomotives built in 1882 for the New York Central & Hudson River Railroad. The preceding class of large locomotives had driving wheel axle loads of 26,500 lbs., while to-day, 1905, several locomotives are in service with 55,000 lbs. per axle.

Mr. William Buchanan, superintendent of motive power, New York Central & Hudson River Railroad, in 1889 designed his famous locomotive, No. 870, with 80,000 lbs. upon the two pairs of driving wheels, 40,000 lbs. upon the forward truck, and 80,000 lbs. upon the tender, when filled with coal and water,—the first 100-ton locomotive.

The stiff 5-inch 80 lb. rails made so smooth and stable a track and reduced the train resistance to such an extent, that on Nov. 30th, 1891, the "Empire State Express" was installed,—the most famous long distance train, the educator of the world in practical rapid speeds. The distance from New York to Buffalo, 440 miles, was run, including three stops and two changes of locomotives, and 28 "slow downs," in 510 minutes, or eight and one-half hours. This schedule was continued until the autumn of 1895, when the time was shortened fifteen minutes, and has been since maintained.

The weight of the locomotive and four coaches was originally 270 tons, which has since been increased.

The train resistance, as indicated by the Clark formula, as was well known before attempting to run the train, proved to be much in excess of the facts. The foreign technical journals did not accept the results for some years.

Railroad officials have been quick to see the decided advantages of the stiffer and heavier sections, from the pioneer 5 inch 80 lb. rails, and replaced their 4.5 inch by 5 inch sections of 80 lbs. or more weight per yard. The enlargement of the locomotives made great progress on the stiffer rails, which had not been possible on the light steel sections, owing to their weakness as girders.

The replies of the railroad companies to the inquiries for the International Railway Congress, Seventh Session, Washington, D. C., May, 1905, show that in the past fifteen years on the stiffer rails the locomotives have doubled in axle and total loads. The possibility of doubling the weight of the passenger, express and mail trains, and run them upon schedules but little slower than the high speed trains, has been equally and perhaps more important to the railroads and community.

The reduction of the undulations in the track, as shown by my Track Indicator, from 6 to 8 ft. per mile, in 1881, on the light and limber rails, to 2 and 3 ft. per mile in 1900 on the stiffer and stronger rails, on the same road bed, measured by the practical results attained, has been doubling the capacity for axle loads and volume of traffic.

Freight trains of 3000 and 4000 tons, on lines of moderate gradients, are possible only on tracks of great combined stability and smoothness.

Railroad officials have taken advantage of such possibilities, as the only way earnings could be secured, from an average freight rate of less than one cent per ton mile.

The results attained by the introduction of the stiffer rails in the same road bed show that it has been the best, quickest and most economic way that the railroad companies could increase the stability and capacity of their roads.

I was able to estimate and state the limited undulations in the track of the stiff rails which would be shown by my Track Indicator, before the pioneer 5 inch 80 lb. rails were rolled. They denoted higher standards than had been previously attained, and to officials seemed improbable. The computed results for the Boston & Albany Railroad with stiff rails and

good material, were that the condition of track would show between the 15th and 16th lines on the condensed diagram. These were stated in 1883.

Mr. William Bliss, president of the company — a Harvard graduate — commenced to lay the $5\frac{1}{32}$ inch 95 lb. rail in 1891, and completed the entire track in 1897. The average sum of the undulations for the track inspection of that year was $15\frac{42}{100}$ lines on the condensed diagrams. I had made all of the rails at the mills of high carbon steel, and lengthened the anvil blocks on the straightening presses, and the rails were finished smooth. It was known what was required, and achieved.

The increased smoothness of track, for maintenance and operations, saved the cost of relaying with the 95 lb. rail, in less than seven years.

Fig. 2 shows a diagram of the surface undulations of the

Fig. 2. Diagram of Main Line tracks, 1881. Undulations eight feet per mile. Vertical scale actual. Horizontal scale one inch to fifty feet, in the original diagrams. Figs. 2 and 3 reduced to two thirds size.

track in 1881 of 8 ft. per mile, where each joint gave a shock to the passing wheels.

Fig. 3 shows a diagram of 1895, of limited undulations, the

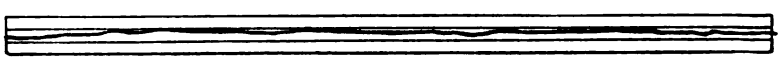


Fig. 3. Diagram over same track in 1900, laid with six-inch 100 lb. rails Undulations under same wheel loads one foot nine inches per mile. So smooth, the three tee joints do not produce shocks to the passing wheels.

joints so smooth as not to be indicated.

The opportunity to test the value of smoothness of the track in running passenger trains of over 700 tons is so infrequent, that the following is of interest as an achievement.

The heaviest passenger train on record which has been run at a speed exceeding 60 miles per hour was the "Southwestern Limited," on the New York Central & Hudson River Railroad, Aug. 19th, 1899. The travel was heavy, and several extra cars were added, forming a longer and heavier train for that day than usual. There were 16 cars and coaches, making the total length of the train from the tip of the pilot to the rear buffer 1212 feet, nearly one quarter of a mile. The total weight was 1,840,000 lbs. or 920 tons. The schedule time of the train, from New York to Albany, to make two stops and five slow-downs, was 3 hours and 15 minutes, to run 143 miles. The train was made up on two different tracks at the Grand Central Station, and was 5 minutes late in leaving. The stop at Harlem required one for the front of the train, then a second for the rear. The actual run was made, including the stops and slow-downs, in 3 hours and 12 minutes, and a speed of over 60 miles per hour was attained at several places.

The engine was a 10-wheel type, 40,000 lbs. on the truck, 128,900 lbs. on the drivers, which were 70 inches in diameter; tender 102,000 lbs.; total, 270,900 lbs. Cylinders 20 by 28 inches. Steam pressure 200 lbs. The stremmatograph tests of the unit fiber strains in the rails, under the passing locomotive, show per lb. of static load about 15 per cent. less than those of the 8 wheel type, when doing proportional work, a fact of importance for heavy trains.

On the lower portion of the road 100 lb. rails were in service, to Dutchess Junction, 57 miles, and from there to Albany new $5\frac{1}{8}$ inch 80 lb. rails had been recently laid. These were finished smooth at the mills, and had been in the track a sufficient time to be in excellent surface.

The train resistance proved to be less than the usual estimates, in part due to making the trackmen's surface and that of the steel as smooth as possible. The rails were laid with alternate 3 tie supported joints. In passing over the track with the track indicator later in the season (October), there was scarcely an indication of the joints shown upon the diagram, from New York to Albany.

The stiffer and better finished rails, both in surface and alignment, have contributed to a reduction of the shocks and oscillations of the cars which obtained on the light and limber rails, thus effecting a saving in train resistance, cost of operating, and adding to the comfort of travel.

Mr. Mailloux, in his able analysis of Train Resistance —April, 1905, number of the JOURNAL, page 47 — states that —

"The average effective fictitious grade, due to track hysteresis, in case of a car or train, is affected by and depends upon so many things, that the study of the yielding effects produced at a single wheel is far from sufficient to give an adequate idea of the phenomenon as a whole or to furnish a clue to the amount of total resultant effect on the train resistance in each case."

This coincides with the important principle of the total load of the locomotive or car distributed by several wheels, each constraining the wheels either side, in opposition to the opinion of independent single wheel loads.

This forms the distinctive feature of American practice, which I have long considered as the basal principle. The results of service secured in the transition from the light and limber sections to the stiff and heavy rails prove, there are principles underlying the present practice, which need investigation for elucidation to explain what has been achieved.

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Editorial.

The development of the Puyallup River water power described in this issue is characteristic of the present western practice. Similar installations are frequently used in the

reclamation of arid lands where, in preference to carrying water in flumes, water power is developed and the power is transmitted electrically for pumping from wells.

During its last annual meeting, the American Electro-Chemical Society held one of its sessions in Pierce Hall and afterwards was received by President Eliot and tendered a luncheon in the Union.

Those of our readers who are interested in the Panama canal, will be glad to know that Gen. Henry L. Abbot has just published a book on the "Problems of the Panama Canal."

Graduate Notes.

J. P. H. Perry, '03, has recently been connected with the completion of a large concrete bridge on the Chicago, Burlington & Quincy R. R., at Big Rock Creek, near East Plano, Ill. The bridge was built in freezing weather and as a means of ensuring prompt setting of the cement the whole structure was heated by steam. An account of the bridge appears in the Railway and Engineering Review for December 12, 1903.

K. E. Adams, '03, is now an assistant in the Engineering laboratory. He is also working with Mr. E. D. Leavitt, M. E., in Cambridge.

S. Cunningham, '01, has announced his engagement to be married.

J. W. Coolidge, '01, has left the American Locomotive Company in Schenectady and is now in the office of the Superintendent of Machinery of the Louisville & Nashville R. R. Co. Address, 722 West Chestnut St., Louisville, Ky.

G. C. Kimball, '00, is assistant chief engineer of the American Sheet & Tin Plate Co. Frick Building, Pittsburg, Pa.

J. A. Moyer, '99, has lately published a second edition of his Descriptive Geometry, revised very thoroughly and more than doubled in size. The left hand pages are reserved for the text, while on the right appear some 77 illustrations and blank pages for notes. In the Engineering News for

May 18, 1905, p. 535, Prof. Henry S. Jacoby of Cornell speaks very highly of this book. He especially commends the logical order of the problems and the numerous graded exercises which are admirably suited for use in the class-room. As a whole, he considers the book "well adapted to the needs of engineering colleges, and in a number of important features the most satisfactory one now available."

Architectural Notes.

For the recent examination for the Julia Amory Appleton Fellowship in Architecture four candidates presented themselves, of whom, however, one withdrew before the examination, leaving A. E. Hoyle, '04 A, R. W. Varney, '04 A, and H. E. Warren, '04 A. These three candidates were first required to pass an examination on a special period of architectural history. The subject for the examination in design was an Atheneum "in an important city which is engaged in extensive civic improvements." "The Atheneum is a corporation whose building is to contain a library, an art gallery and a lecture room." The competitive designs were first submitted in the form of preliminary eight hour sketches. The candidates were then given three weeks for the preparation of the final drawings.

These were examined by a committee appointed by the Department of Architecture with the approval of the President, consisting of Mr. R. S. Peabody, Mr. E. M. Wheelwright and Mr. R. C. Sturgis, acting with the instructors in the Department. After a careful examination, the committee unanimously decided to recommend Mr. H. E. Warren for the fellowship. Mr. Warren who lives in West Somerville is twenty-three years old and came to the Department of Architecture from the Rindge Manual Training School. He graduated from the Department of Architecture in 1904 with a "magna cum." He has spent the last year in post graduate study in Architecture, holding one of the Austin Resident Scholarships. Mr. Warren will spend two years of study and travel abroad and will work during a large part of his time at the American Academy in

Rome. The holder of a Fellowship in Architecture is required to submit monthly reports of his progress and to send at the end of each half year a measured drawing of some monument of architecture, which must be approved by the Department. He is also required to make during his stay in Europe, a special study of a single building or group of buildings, and on his return must present a written essay, illustrated by drawings, embodying the results of this study. Mr. Warren expects to go to Rome in the early fall.

J. E. Somes, Jr., '01 A, and E. M. Parsons, '03 S., have recently established themselves in practice in the Paddock Building, 101 Tremont St., under the firm name of Somes and Parsons.

W. S. Parker, '99 A, is in the office of Messrs. Sturgis and Barton in Boston.

E. B. Van Winkle, Jr., '04 A, is in the office of Messrs. Trowbridge and Livingston in New York City.

The firm of Whitfield and King of New York, of which H. D. Whitfield, '98 A, is senior partner, was employed for the design for the new library at Tufts College in Medford, near Cambridge.

FIG. 1.—CONCRETE ARCH.
CHICAGO, BURLINGTON & QUINCY R. R., PLANO, ILLINOIS (page 140)

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THE HISTORY, MANUFACTURE, AND PROPERTIES OF HARD DRAWN COPPER WIRE.

BY THOMAS B. DOOLITTLE.

THAT the adaptation of a well known principle to meet conditions sometimes leads to important results is well illustrated in the story of the raising of the Obelisk in the Piazza di San Pietro, Rome. The populace were commanded under penalty of death to keep silent. At a critical moment, when the Obelisk had nearly reached a perpendicular position, the ropes proved too long. A sailor cried out "Aqua alle funi" (wet the ropes). This was done, and the shrinking of the ropes set the Obelisk squarely on its base. It will be remembered that the sailor (Bresca) received a reward instead of the penalty.

Hard drawn copper wire was the result of an adaptation rather than a discovery, although many of its valuable properties were not appreciated until after it had been in service several years.

It is the common knowledge of all who are familiar with the manipulation of copper that the process of drawing it into wire serves to harden the surface. Thus it will be seen that the experiments which resulted in the so called hard drawn copper wire were based upon a well known principle, although the application of this principle had never been made use of for the final product. The writer was familiar with this phenomenon at the time he entered the field of electricity; therefore, when it was disclosed to him that copper was not only one of the best conductors of electricity but was the cheapest in conduc-

tivity, or per mile ohm, it was only left for him to determine whether or not this hardening process could be made available, in order that copper wire should be comparable to iron in its ability to stand the strain of its own weight when strung on poles, and, in addition thereto, the weight of sleet or snow and wind pressure. There was no mathematical road to determine this factor; therefore, it was simply a case of "cut and try."

First, the size of the finished product was fixed upon (#12 B. & S. gauge); then it became a matter of experiment to determine the size of the annealed copper rod which, when drawn to this predetermined size, should possess the proper tensile strength and the required torsional property. It was also necessary to determine the number of "holes" or reductions that should intervene in the process of drawing in order that the structure or fibre of the metal should not be injured during the process. Too much force would result in granulating the metal and thereby impairing its tensile strength. The experiments proved all that could be anticipated, and a sufficient amount of hard drawn copper wire was manufactured to equip the lines necessary to connect all of the mills, offices, and residences of officers of The Ansonia Brass and Copper Company, in whose wire mill these experiments were made. A telephone switchboard was set up in the brass mill of that company, and an operator answered calls and made connections. This work was begun in November, 1877.

Although the product is known in the trade as hard drawn copper wire, and properly so known — as the name indicates its property of hardness and the method of manufacture, — the name has no antonym or contra-term because soft drawn copper is a misnomer; the very process of drawing eliminates the quality of softness and makes it hard.

Prior to its introduction for aerial electrical conductors, there was very little, if any, call for the hard product. Copper wire was usually annealed after drawing, and sold in that form. Copper alloyed with other metals was, and is now, used in the manufacture of hard or "spring wire."

Scepticism on the part of electricians and generally in scien-

tific circles, as to the practical value of this adaptation, prevented its being adopted to any extent, except the few circuits that the writer introduced into the Bridgeport, Connecticut, telephone exchange, until seven years afterward.

In 1884 the writer was commissioned to construct an experimental metallic circuit of copper between New York and Boston. The wire for this circuit was drawn under his personal supervision in the wire mill of the Bridgeport Brass Company. The total cost of this experiment was, in round numbers $70,000. After the experiment was concluded, the wires were turned over to the intervening telephone companies for local use, and immediate steps were taken to build the New York and Philadelphia long distance telephone line. The miles of hard drawn copper wire now in use for all electrical purposes are counted by millions.

The first recorded employment of copper as a line conductor was its use by Prof. Morse in his experimental telegraph line between Washington and Baltimore. The ordinary market wire was used but, for the reason that it would not sustain its own weight, it was abandoned and iron wire was substituted. The next of record was strung by the Western Union Telegraph Company, in New Jersey. In this case, also, the ordinary copper wire was used, but an attempt was made to increase its tensile strength by twisting a pair of wires into the form of a rope. This did not prove a success and was abandoned for the same reason as the other. In the early seventies many experiments were tried in attempts to make available for aerial line conductors the superior conductivity of copper. In each case a steel wire was employed for tensile strength. In one case a copper ribbon was wound spirally around the steel wire. On exposure to the elements a chemical action was set up that quickly destroyed the steel core. This ribbon was afterward tinned, but with unsatisfactory result. In another experiment the copper ribbon was folded longitudinally. The last and most successful in this line of experiment was the process of electroplating the steel wire with copper. This was put in service by the American Rapid Telegraph Company, but in a few years it

also proved unsatisfactory and was abandoned. Therefore it will be seen that the first successful employment of copper wire for electric line conductors was on the telephone lines of The Ansonia Brass and Copper Company in 1877, and the Bridgeport, Conn., telephone exchange in 1878. The next was on the line between New York and Boston in 1884. The latter experiment was an immediate success, and hard drawn copper wire was, within a few months, adopted throughout all civilized countries.

In recent years great improvements have been made in the process of manufacture, which cover all operations from the ingot to the finished product. At the time recorded above it was the practice to roll a billet of copper, say of six or eight inches in width, into a long sheet and then, after being annealed, it was taken to a slitting machine and slit into square rods. These rods were tapered by means of a hammer, in order that they might be inserted far enough through the drawing die to be grappled on the opposite side, after which they were ready to be drawn into wire. This method of starting with a square rod had a distinct disadvantage for the reason that the corners were likely to lap and fold over in the process of drawing, thereby producing flaws or bad places in the wire, these flaws becoming more and more troublesome in the smaller sizes of wire. After having been drawn through a certain number of "holes," the surface of the wire becomes hardened to an extent which requires that it should be annealed before any further reduction in size is practicable. The new process is substantially as follows: —

The copper is received from the smelting works in the form of wire bars, which are approximately fifty-four inches long, with an average diameter of about three and three-fourths inches, and weigh about two hundred pounds each. These are delivered as commercial copper wire bars.

The first operation is to put the bars into what is termed a "continuous furnace," the bars going in at one end of the furnace and taken out at the other. In their passage through they are heated to about 950° Centigrade, at the rate of about two bars per minute.

The heated bars are then put through a series of grooved rolls. Each succeeding groove being smaller, it results in a reduction of the three and three-fourths inch bar to a diameter of five-sixteenths inches. These are now called rods, and are taken up on a reel in the form of a coil about thirty inches in diameter. These coils are then taken from the hot-rolling department, and are cold at that time. They are then plunged into a bath of sulphuric acid and water for the purpose of removing whatever oxide has been formed in the hot-rolling operation. After about twenty minutes in this solution, the oxide is removed and the rods are then taken and thoroughly washed with clean water under a high pressure from a hose; after which they are immersed in a vat containing a lubricant of tallow and soap. The rods are now ready for the drawing process.

The rods are substantially drawn on what is termed by wire manufacturers a "continuous wire drawing machine." That is to say, the five-sixteenths inch rod goes in at one end of the machine, and, after passing through several dies, each one reducing the diameter and hardening the wire, it finally is drawn around a block to the finished size, say .104″.

In making this reduction, the copper is reduced in diameter from #1 wire gauge to #12 wire gauge, or, in technical terms, the wire is "eleven numbers hard." This process gives the wire the greatest amount of tensile strength possible from commercial copper and yet preserve its elasticity. The cost of production is enormously reduced by the new process. Whereas, under the old process, a very skilled workman was required for each single drawing, an attendant is now able to care for several continuous drawing machines that are run at a speed, unapproachable by the old method. In the smaller sizes of wire, diamond dies are employed which, in themselves, represent a very considerable investment.

Commercial copper in its soft state has a tensile strength of about 28,000 pounds per square inch, with an elongation of about thirty-six per cent., and by the cold-drawing process above described, the tensile strength is increased by each number drawn, and the elongation is reduced; therefore when the

copper wire is drawn eleven numbers hard, it has a tensile strength of about 64,600 pounds per square inch, with an elongation of about one per cent. The wire is then taken from the wire-drawing blocks, so-called, and is carefully inspected for tensile strength, elongation, torsion and conductivity. The inspected wire is then carefully packed by wrapping each coil with burlaps, so that it does not become bruised or damaged in any way by transportation.

The cost of hard drawn copper wire fluctuates with the price of ingot copper, and at present writing is quoted at sixteen cents per pound. The relative cost of copper and iron wire, say of #12, is three and three-fourths cents for iron and sixteen cents for copper.

The advantage of copper over iron, besides what is shown in the table below, is that it is practically indestructible except from mechanical injury, and, if it receives mechanical injury, it can be made over into new wire at a cost of about two cents per pound, while iron, which is subject to rapid deterioration from rust, is worthless when taken down.

The output of hard drawn copper wire has steadily increased from year to year.

The comparative properties of #12 N. B. S. gauge copper and iron wire are given in the following tables, this being the size in the largest general use as telephone toll line conductors.

No. 12 N. B. S.	Diameter in Mills	Resistance per Wire Mile 68° F. Ohms	Inductance per Pair Mile Milhenries	Effective Resistance per Wire Mile Ohms	Electro Static Capacity per Pair Mile Micro microfarods	Miles equal to 1 Mile Hard Drawn Copper for Telephone Transmission
Soft copper	104	5.1	3.66	5.1	8220	1.02
Hard drawn copper	104	5.2	3.66	5.2	8220	1.00
Iron B. B.	104	36.0	18.00	47.0	8220	0.26

No. 12 N. B. S.	Diameter in Mills	Weight per Wire Mile lbs.	Tensile Strength in Pounds	Torsion in 6 inches	Elongation Per cent.
Soft copper	104	173	290	50–75	40.
Hard drawn copper	104	173	550	25–45	1.
Iron B. B.	104	153	450	45	18.

The above figures represent average commercial conditions. The soft drawn copper wire is assumed to have a conductivity of 99 per cent. of that of pure soft copper, while that of the hard drawn is 97 per cent.

The wires of a pair are supposed to have a separation of 12 inches on centers. In calculating the inductance and effective resistances, a frequency speed ($2\pi n$) of 5,000 has been taken, while assuming a permeability of 100 for the iron wire.

Much of added interest could be written were the writer to disregard the individual trade secrets that must be respected.

The following manufacturers are producing hard drawn copper wire:

John A. Roebling's Sons Company,
Coe Brass Manufacturing Company,
Ansonia Brass and Copper Company,
Holmes, Booth & Haydens Company,
National Conduit and Cable Company,
American Steel and Wire Company,
The Waclark Wire Company,
Standard Underground Cable Company,
American Electrical Works,
The Bridgeport Brass Company.

I am indebted to the officers of these companies, and also to Mr. Charles F. Brooker and Dr. Hammond V. Hayes, for valuable assistance in the preparation of this paper.

Pine Orchard, Connecticut,
Nov. 1st, 1905.

THE PLANO ARCH.

By John P. Hazen Perry, S. B. '03.
Jun. Am. Soc. C. E.

Three quarters of a mile east of Plano, Illinois, the main line of the Chicago Burlington and Quincy R. R. crosses Big Rock Creek. At the crossing point the stream flows through a valley about a thousand feet wide and sixty feet deep. Since the construction of the railroad in 1852–53, five bridges, including the present structure, have spanned the valley. The last bridge (Fig. 3)—built in 1882 to replace a 185 ft. Howe truss—consisted of a main span of a square ended, pin-connected, deck Pratt truss 99 ft. long, and four deck-girder spans, two at either end; making a total length of 275 ft. This structure was deemed too light for modern traffic requirements and in August, 1903, the contract was let for the replacing of this bridge with a concrete arch.

The plans of the new bridge called for an arch of 75 ft. clear span with wing walls giving a total length of 210 feet. The arch is 3 feet thick at the crown and is heavily re-inforced throughout with Johnson corrugated bars. The bridge was designed to carry the heaviest loads and was calculated according to Mr. A. L. Johnson's formulae for reinforced concrete.

This paper will deal with the construction of the bridge. Before going into an account of the work in its progressive stages a few notes on the materials used might be appropriate.

The concrete was used in two proportions. For all parts of the bridge, except the arch ring, the mixture was 1–3–6, cement–sand–stone; for the arch ring 1–2–4 was used. The cement was, for all except a small portion of the foundations, "Owl" Brand from La Salle, Ill. The sand came from the great Steward pit, an opening in the glacial drift which overlies all this part of Illinois. Stone was furnished by Doleese & Shepard from their Hawthorne quarries just out of Chicago. The

contractor obtained permission to use gravel in the proportion one of gravel to two of stone for all parts of the bridge except the arch ring. The "mix" then became 1–3–2–4, cement–sand–gravel–stone. The gravel was brought from the Steward pit. At first the product of the pit was screened to give the proper proportions of sand and gravel, 3–2. After screening perhaps 500 yards it was found that the pit was yielding almost exactly the proportions desired and no further screening was resorted to except to get the sand for the arch ring.

The mixture used was very wet, water being added to the mixer until the concrete was like heavy slush. Care was taken to make the little concrete tram cars absolutely tight at the bottom so that none of the liquid "fine stuff" — cement and sand — should be lost in transit from the mixer to the forms. This very wet mix gave, with but ordinary care in spading the stone away from the forms, a most excellent face sufficiently smooth nearly everywhere to show the grain of the wood in the forms. Upon resuming work on the top of concrete, already hard, wire brushes and a powerful hose were used to remove "la laitance," the peculiar scum which rises to the surface of very wet concrete and works so adversely to the bonding of the new concrete with the old.

The reinforcing bars were corrugated steel bars seven-eighths in. square and three-fourths in. square. In all 60 000 lbs. were used in the bridge giving a length of 30 000 ft. The bars are shown in Fig. 2. They came in lengths averaging about 25 ft. requiring two men to handle each piece. No attempt was made to paint them or protect them from rust, it being thought that the bond obtained by rough rusty bars was better than with painted ones.

The method adopted for building the arch without interrupting traffic was unique. The C. B. & Q. R. R. being double tracked the natural way of handling the problem would have been to discontinue the use of one track throwing all traffic on the other and use the first track to construct half of the new bridge — transfer all traffic to the new bridge and use the second track, now abandoned for completing the job. The

railroad company in this instance, however, insisted on maintaining double track traffic. It was therefore decided to leave the old bridge intact, except for the lateral and sway bracing, and build the arch span up through the truss rods. Fig. 2 shows the forms for these holes. Falsework was erected on the deck of the arch and traffic thrown thereon. The pins connecting the truss members were knocked out; the rods drawn up through the holes by a derrick and the holes concreted, the bridge filled,

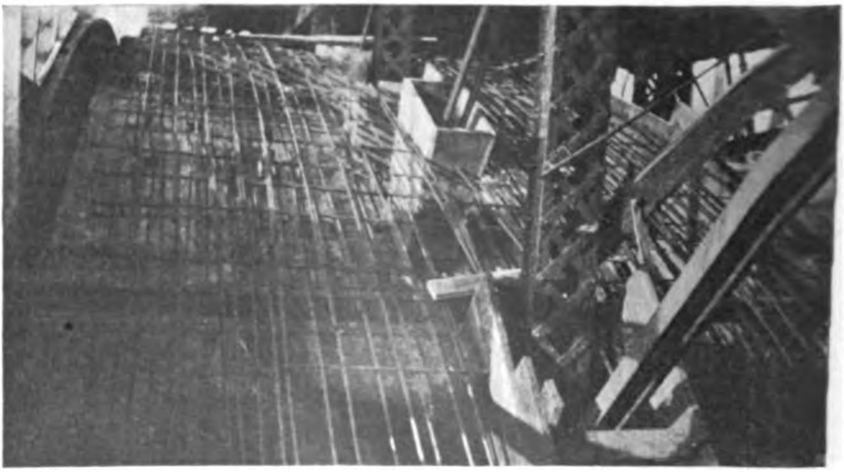

FIG. 2.

and allowed to settle; the track ballasted up and the centering and falsework removed.

The railroad company began operations in May, 1903, by digging the pier pits and driving the foundation piles. The old masonry piers (Fig. 3) were to be incorporated in the skew back and foundations of the new arch. Small sheet-piling cribs were built and excavations carried to five feet below stream bed and the concrete brought up about water level.

In August the contractor took charge of the work.

His force was organized under two foremen into a carpenter gang and a concrete gang. Eventually the carpenter foreman took charge of the work, supervising everything. For mixing

his concrete the contractor used both an "Olsen" and a "Drake" mixer. Power was furnished by an upright boiler. For transporting the concrete, tram cars of about a yard and a half capacity were used. Temporary tracks were built from the mixer to the place of deposit and the cars run out on them by man power. For handling his lumber the contractor made use of the high fill at one end of the bridge. (See Fig. 4.) The timber was dumped from the railroad cars on to the side of this fill whence they rolled out on a meadow practically in position for cutting and framing. When the bents and centers were ready for placing they were pushed into the stream, floated down against the falsework piles and hoisted into position with block and tackle.

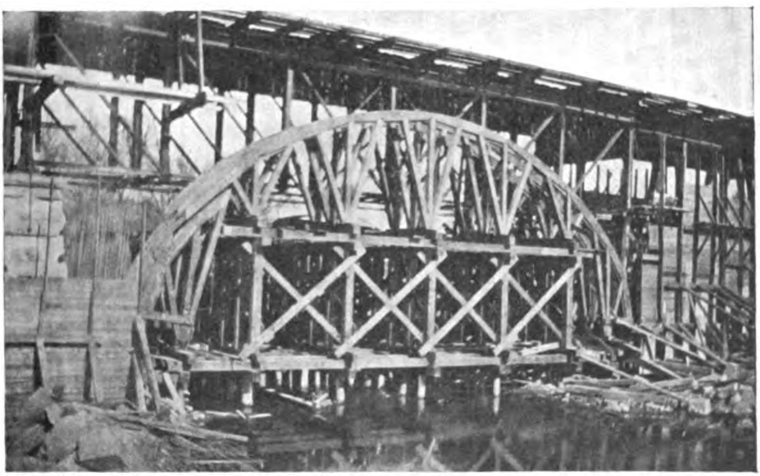

Fig. 3.

The falsework (Fig. 3) consisted of heavy bents resting on piles. On the falsework were the centers. The pile caps, falsework and centers were made of 12 in. by 12 in. timber. The centers were made in fan shaped sections and were hoisted into place and wedged to exact position. Fig. 3 shows three of the arch rings in place and nearly all connected up. The wedges were of oak beveled both ways and well soaped. When three of the twelve centers were in position they conformed to

the line of the intrados of the arch and checked by plumbing down from a base line laid out on the edge of the bridge ties on the deck of the old bridge. From this base line ordinates were measured to the points on the arch ring and all tightened up securely. From these centers as a guide the remaining ones were set and lagged. The lagging was of 3 in. stuff planed to a bevel to make tight joints. The carpenter work was excellent, the centers checking very well indeed.

While the falsework and centers were being made ready the contractor started work on the concrete and on the cutting of the masonry piers. The latter presented an unexpected difficulty. The stream faces of the piers were to be cut into steps, eleven in number, and into the base of each step were to be set 4 ft. corrugated bars; the idea being to bond the arch skew-back and foundation with the old pier, there being an opportunity for unequal settlement and consequent cleavage. The contractor told the writer that he had estimated the cost of this stone cutting at one hundred dollars and the time at two weeks. It actually came to one thousand dollars and took eight weeks to complete. The trouble lay in the character of the stone constituting the piers. They were built in 1882 of Aurora limestone, which is famous locally for the way it hardens with exposure. When the stone-cutters undertook to cut the steps specified they found that between the hardness of the stone and the way in which it was bound in courses they could do nothing but chip the surface in small spalls. An Ingersoll-Sargent drill was called into use for drilling the 4 ft. holes for the main reinforcing bars coming over the extrados of the arch — and also to cut four steps in the face of each pier by drilling 4 ft. holes at 2 in. centers and taking the rock out with plugs and feathers. The steps that were thus cut were well up on the pier and in order to make a bond below them the face of each pier was cut into prismoidal shaped holes at the joints, the cutting being easier there because of less bonding effect. The nose and back of each pier were also cut to aid the concrete in bonding with the piers. The work at these joints consisted of cutting away alternate

courses to a depth of about 8″. Fig. 3 shows this work — the back of the pier at the left of the cut.

The general method of placing the concrete was as follows:— The wing walls, one at a time, were brought up to about the elevation of the top of the old piers. At the same time the arch foundations and skew backs were carried up to the springing line. Then the arch was turned and the wing walls carried up to within a few feet of the finish line. The spandrel walls on the arch ring were then brought up to the same level and the

Fig. 4.

remaining few feet of wall and coping put on over the entire length.

The forms for the wing walls were braced by struts from the outside and were wired together as well. The temporary braces were used to hold the forms apart till filled with concrete. The face wall forms were made of 2 by 8 in. tongued and grooved yellow pine plank. The back wall forms were of rough lumber 2 by 8 in. When the wing walls got up so high that struts were no longer practicable knee-bracing was resorted to. Both kinds of bracing are shown in the accompanying cuts. The line of the completed walls was very good — there being scarcely

any bulging. In all about 500 000 ft. B. M. of lumber was used on this piece of construction and 300 000 ft. of it was available for use on other work at the end of the job.

The arch ring was turned in parallel strips. It was required that there be no transverse joint planes and to fulfill these specifications it was necessary to have continuous work on the ring. This with the plant on the ground was impossible. The daily average of concrete placed was about 90 cu. yds. In the arch ring were about 900 cu. yds. There was not enough labor available to make it possible to run day and night for five days. The arch was therefore divided into several longitudinal strips. Bulkheads were erected on the lagging and molded to form a key between each strip. These bulkheads were braced against the truss members. In filling one of these rings batches were deposited first at one end and then at the other end of the arch — to prevent unequal loading and consequent unequal thrust on the centers. Work was carried on continuously until the arch ring was completed. Only once was it necessary to quit work in the course of turning an arch ring. A blizzard came up during one night, when the ring was about half complete, and effectually clogged the plant — tracks, cars, and men. A radial joint was bulkheaded up and filled to full depth of the arch and the top of the concrete boarded up and left till the storm ceased when work proceeded to the completion of that particular strip.

Most of the concrete was deposited from the top of the old bridge. When the fall was more than fifteen feet chutes were used. If the chute had to be on a slant a curtain door was rigged over the mouth of it to prevent the stone from jumping out away from the fine stuff as it all dropped into the forms. Most of the chutes were of wood hastily knocked together by the carpenters. In turning the arch, however, much use was made of an iron chute or trough which could be moved in among the old truss members and reinforcing bars with facility. The reinforcing rods (Fig. 2) made the shoveling of the concrete very difficult on the drum of the arch. The men handling it had to crouch in between the extrados and intrados bars.

All of the arch ring and the major part of the wing walls were

built during freezing weather. The precautions taken to avoid freezing of the concrete were simple and effective. The sand and water were heated as much as possible. The former was handled as follows. At the sand pile was laid about 30 ft. of 2-ft. iron stack or thin pipe open at each end with a stack rigged near the center for better draught. A roaring fire was kept in this stack night and day and the sand heaped up over it to a depth of a couple of feet all around. In this way sand was kept very hot, often to a dull red. The water was heated by a steam hose run into a barrel at the mixer. The stone was not heated, care only being taken to keep the stone pile free from snow so that thawing in the middle of the day and freezing at night should not bond the stone into an ice heap. In the forms a steam hose was kept going. Its use was varied. In the arch ring there were the reinforcing rods sticking out of the concrete which acted as so many pipes to conduct away the heat. These rods were kept under steam as much as possible, the man with the hose working at the opposite end from where the concrete shovelers were. Further, the concrete in dropping into the forms spattered the rods and the forms and this spatter immediately froze and the steam hose was about the only thing which would remove it. Then also after a snow storm the steam hose removed the ice from the forms very quickly. One of the arch rings was turned one night when the temperature was 8° below zero. The concrete showed no signs of freezing. A thermometer put with its bulb just beneath the surface of concrete which had been in position three hours registered 35° and when pushed down about four inches into the concrete the reading was 68°.

When the arch ring was completed it was deemed advisable to heat it. Concrete sets very slowly when frozen solidly. Once it gets its initial set, say inside of four hours after mixing, it is safe from harm from freezing. It will not set up hard until the frost is out of it. On this piece of work the arch ring was completed in January and the spandrel walls a month later. The railroad company was in a hurry to get unrestricted use of the bridge and heating was resorted to to give summer conditions about the arch and thus allow it to set and be ready to take its load.

The falsework just at the bottom of the centers was floored over and the ends of the room thus made by the floor and the arch, were boarded up and all tar-papered to keep out the wind. In this loft like space, as close to the arch as possible, was 5000 feet of steam piping. An old locomotive boiler was brought from the Aurora shops and set up temporarily to supply steam for the heating plant. The top of the arch was enclosed by means of the spandrel walls and partitions at the ends and between the spandrel walls and the floor of the old bridge. With this complete housing in of the arch a temperature of from 96° over the arch to 100° under the arch was maintained for a mouth completely drying the arch.

When traffic was thrown on the temporary bents on the arch and the old bridge removed by the "wrecker" the holes in the arch ring were filled with concrete and the filling of the bridge started. The dirt for this purpose came from widening a nearby railroad cut. When the falsework was removed no settlement was observable in the crown of the arch.

The plans of this bridge were drawn in the office of Chief Engineer W. L. Breckenridge under the direction of C. H. Cartlidge, Bridge Engineer, the contractor was G. H. Scribner, Jr., of Chicago. The writer was in charge of the work for the railroad company.

THE DISTRIBUTION OF PRESSURE AND CURRENT OVER ALTERNATING-CURRENT CIRCUITS.

By A. E. Kennelly, D. Sc.

When an alternating-current circuit for the transmission of power is operated at any of the usual commercial frequencies not exceeding 60 cycles per second, it is well known that the distribution of pressure and current in the circuit may be computed, within a degree of accuracy sufficient for practical purposes, by collecting all of the capacity distributed along the lines

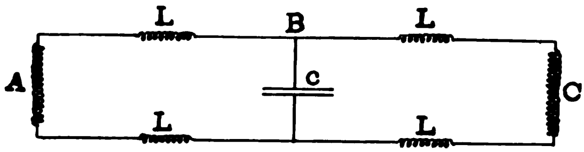

Fig. 1. Diagram of an Alternating-Current Circuit with the entire Line Capacity centered at B, and the resistance and inductance divided between the four choking-coils L, L, L, L.

into a single lump, or imaginary condenser c, midway along the circuit, as indicated at B in Fig. 1, and collecting the distributed resistance and inductance on each side of this condenser into imaginary choking coils L, L, L, L. By this method of dealing with the circuit, the line becomes a mere collection of condenser and choking-coils. The drop in pressure over the lines, as a whole, may then be determined for any given alternating-current load, even for the longest circuits at present in use for electric power transmission.

As a convenient modification of the above plan, the metallic circuit of Fig. 1 may be regarded as a pair of single-wire circuits, each with a perfectly conducting ground-return circuit, as shown in Fig. 3, and each having twice the localized condenser capacity ($2c$), compared with the condenser (c) of Fig. 1. Each ground-return circuit in Fig. 3 has also half the e. m. f. and

impedance of the metallic-return circuit in Fig. 1. The process of transition in conception from the single metallic-return circuit of Fig. 1 to the equivalent pair of independent ground-return

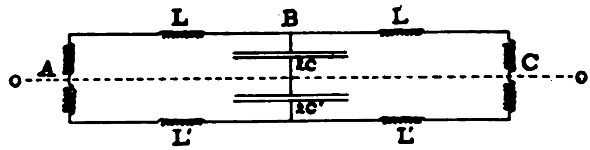

Fig. 2. Division of the circuit of Fig. 1 into two equal and symmetrical portions about the neutral mid-plane 00 of zero potential.

circuits of Fig. 3, is indicated in Fig. 2; where the metallic circuit is first divided symmetrically about a neutral midplane of zero potential, or earth potential.

It is well known that any interlinked multiphase system of circuits may likewise be resolved into independent single-phase single-wire lines with imaginary perfectly conducting ground-return circuits; so that it suffices to solve the problem of pressure and current-distribution for a simple single-phase single-wire ground-return circuit in order to determine the corresponding solution for any two-wire metallic circuit; or for any interlinked multiphase and multiple-wire circuit. For

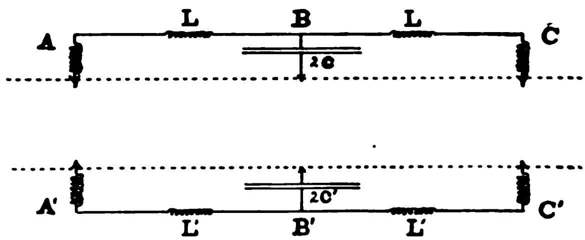

Fig. 3. Analysis of the double-wire circuit of Fig. 1 into two equivalent single-wire circuits A, B, C and A′ B′ C′, each having twice the condenser capacity of the circuit in Fig. 1.

this reason only such single-phase single-wire circuits as are indicated in Fig. 3, need be considered in what follows.

As already stated, the treatment of an alternating-current circuit in the manner of Fig. 3 is permissible for the low frequencies of power transmission. This is because the wave-

length of alternating current at such frequencies is ordinarily hundreds of miles long; so that the longest circuits in use are but fractions of a wave-length, or are short compared with a wave-length. When an alternating-current circuit is short compared with the length of impressed waves, all parts of the circuit present phenomena of nearly the same phase. It becomes unnecessary to enquire into the relative phase of current and pressure at different points along the line, and the line may safely be treated as equivalent to a pair of choking coils with a condenser connected to ground between them.

When, however, the frequency is considerably increased, either by the use of higher impressed frequencies, as in telephony; or in the consideration of harmonics incidental to the usual low fundamental frequencies of power transmission, the wave-length of the current is correspondingly shortened, and the line may no longer be short compared with the impressed wave-length. Under such conditions the treatment by the method indicated in Figs. 1–3 is inadequate and may involve considerable error. A more rigorous analysis must be substituted which deals with the distribution of resistance, inductance, leakance and capacity, in their natural association. Moreover, this more rigorous method has to be resorted to, even for low frequencies, when a higher degree of accuracy is required in the solution of the problem than is necessary for ordinary engineering purposes. The more accurate method is well known under a variety of mathematical forms.* It is, however, the object of this paper to present the method in the form of hyperbolic trigonometry, which appears to be the simplest and most direct. This form follows immediately from the corresponding treatment of continuous-current circuits of uniform resistance and leakance in

* Heaviside's "Electrical Papers." London, 1892. Vol. II, p. 248.

M. Leblanc, Trans. Am. Inst. El. Engrs. June, 1902. Vol. XIX, pp. 759–768.

M. I. Pupin, Trans. Am. Inst. El. Engrs. Vol. XVII, pp. 445–513. May, 1900.

G. A. Campbell, "Phil. Mag." March, 1903.

G. Roessler, Fernleitung von Wechselströmen. 1905.

the steady state; so that the formulae which control continuous current circuits* apply also, with extended meaning, to alternating-current circuits, just as Ohm's law applies not only to continuous-current circuits, but also to alternating-current circuits, when impedance is substituted for resistance in the formula. $I = E/R$.

Every circuit carrying alternating currents of one frequency possesses an *attenuation-constant* a, such that any electric wave of this frequency shrinks in magnitude, or attenuates, to the extent of $\frac{1}{\epsilon^{a}} = \epsilon^{-a}$ in running unit distance over the circuit. If the wave has, therefore, say a magnitude of unity at a given

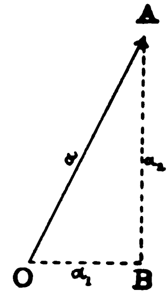

Fig. 4. Analysis of the vector attenuation-constant $OA = a$ into the real part $OB = a_1$ and the imaginary part $BA = a_2$.

point in the circuit, and the unit of length is a mile; then the magnitude of the wave will be ϵ^{-a} after running one mile, $\epsilon^{-a} . \epsilon^{-a} = \epsilon^{-2a}$ after running two miles, and ϵ^{-La} after running L miles. Since the exponent La must be some number, and L is a length, a has the dimensions $\frac{1}{\text{length}}$.

The attenuation-constant a is a complex quantity of the type

$$a = a_1 + ja_2 \quad \text{per mile or kilometre} \quad . \quad (1)$$

so that a_1 is the real part of the attenuation constant and a_2 the imaginary part, as indicated in Fig. 4; where

$$a = \sqrt{a_1^2 + a_2^2} \ \underline{|\tan^{-1}\frac{a_2}{a_1}} = a_1 + ja_2 \quad . \quad . \quad (2)$$

* A. E. Kennelly, Harvard Engineering Journal. May, 1903. pp. 135–168.

If then a wave in running one mile shrinks in the ratio ϵ^{-a}, it becomes multiplied by the factor $\epsilon^{-a} = \epsilon^{-(a_1 + ja_2)} = \epsilon^{-a_1} . \epsilon^{-ja_2} = \epsilon^{-a_1} \overline{|\ a_2}$. That is, the magnitude alters by $\epsilon^{-a_1} = \frac{1}{\epsilon^{a_1}}$ and the phase is retarded by ϵ^{-ja_2} or by a_2 radians, or by $a_2 \left(\frac{180}{\pi}\right)$ degrees. In two miles, the wave will have shrunk in the ratio $\epsilon^{-2a} = \epsilon^{-2a_1} \overline{|\ 2a_2}$; or in the ratio $\frac{1}{\epsilon^{2a}}$ with a phase retardation of $2a_2$ radians. Similarly, after L miles, the wave will have shrunk $\epsilon^{-La} = \epsilon^{-La_1} \overline{|\ La_2}$ or in the ratio of magnitude by $\frac{1}{\epsilon^{La_1}}$, with a phase retardation of La_2 radians. The retardation of phase in one complete wave-length λ miles will be 2π radians, and consequently the wave-length is determined by the relation

$$2\pi = \lambda a_2 \qquad \text{radians} \quad . \quad . \quad . \quad . \qquad (3)$$

or $$\lambda = \frac{2\pi}{a_2} = \frac{6.283}{a_2} \qquad \text{miles or kilometres} \quad . \qquad (4)$$

It is evident that the attenuation constant a of the line, at the impressed frequency under consideration, consists of a real part a_1 affecting the shrinkage in magnitude, and an imaginary part a_2 affecting the shrinkage in phase, such that the wave-length is the quotient of a_2 into 2π. For this reason the imaginary component a_2 is sometimes called the *wave-length constant* of the circuit for the frequency considered.

Moreover, the velocity, rate of advance, or speed of propagation, of the electric waves over the circuit is determined by the relation

$$v = \frac{\lambda}{T} \qquad \text{miles or kilometres per second} \quad . \qquad (5)$$

where T is the periodic time, in seconds, of the alternating current. If n be the frequency of the impressed e. m. f. in cycles per second, $T = \frac{1}{n}$ seconds . . . . (6)

and if the angular velocity of the impressed e. m. f. be

$$\omega = 2\pi n = \frac{2\pi}{T} \qquad \text{radians per second} \quad . \qquad (7)$$

Then $v = \lambda\, n = \dfrac{\lambda\, \omega}{2\, \pi}$ miles or kilometres per second (8)

Or substituting (4)

$$v = \frac{2\,\pi}{a_2} \cdot \frac{\omega}{2\,\pi} = \frac{\omega}{a_2} \quad \text{miles or kilometres per second (9)}$$

On plain aerial wires it will be found that v tends to approach 3×10^5 kilometres per second, or 1.86×10^5 miles per second, the velocity of light in air. In plain underground wires, *i. e.*, underground wires not artificially loaded with inductance, v tends to a lower value, of the order 10^5 kilometres per second, the velocity of radiation in the rubber, paper, or other dielectric employed. With either aerial or underground wires which have been artificially loaded with inductance, the velocity v may be reduced to a small fraction of the free dielectric velocity.

As an example of the above principles, we may consider an aerial line consisting of two # 10 A. W. G. copper wires (diameter 0.1019″ or 0.2589 cm.), interaxially separated by a distance of one foot (30.48 cms.). In this line, the resistance r will be 10.6 ohms per loop-mile = 6.586 ohms per loop kilometre; inductance l will be 3.676 millihenrys per loop-mile = 2.284 millihenrys per loop kilometre; capacity c will be 0.008018 microfarads per loop-mile = 0.004982 microfarads per loop kilometre. Referring these to the equivalent single-wire lines of Fig. 3, each has resistance r of 5.3 ohms per wire-mile = 3.293 ohms per wire-kilometre; inductance l of 1.838 millihenrys per wire-mile = 1.142 millihenrys per wire-kilometre; capacity c of 0.01604 microfarad per wire-mile = 0.009964 microfarad per wire-kilometre. The insulation of the wires may be regarded as practically perfect, or the leakance $g = 0$.

The formula for the attenuation constant is

$$a = \sqrt{(r + jl\omega)\,(g + jc\omega)} \quad \text{per mile or kilometre (10)}$$

where r is the resistance, ohms per mile or kilometre
" l is the inductance, henrys per mile or kilometre
" g is the leakance, mhos per mile or kilometre
" c is the capacity, farads per mile or kilometre
" j is $\sqrt{-1}$

and ω is $2\pi n$, the angular velocity of the impressed e. m. f. in radians per second.

It does not matter whether the constants r, l, g and c are taken from the loop-mile (as in Fig. 1) or from the wire-mile (as in Fig. 3). The same value of a will be found in either case if the values of these constants appropriate to each assumption are inserted in the formula. On the loop-mile basis, the values of r and l will be doubled and that of g and c single. On the wire-mile basis, r and l will become single while g and c will be doubled. The product $(r + jl\omega)\ (g + jc\omega)$ will thus be constant.

In this instance taking the values per wire mile, we obtain for the frequency $n = 200$ or $\omega = 1256.6$ radians per second.

$$a = \sqrt{(5.3 + j\,2.31)\ (0 + j\,2.015 \times 10^{-5})}$$

$$= \sqrt{(5.782 \,\underline{|\ 23°.34'})\ (2.015 \times 10^{-5} \,\underline{|\ 90°})}$$

$$= \sqrt{1.165 \times 10^{-4} \,\underline{|\ 113°.34'}}$$

$$= 1.079 \times 10^{-2} \,\underline{|\ 56°.47'} = 0.010{,}79 \,\underline{|\ 56°.47'} \text{ per mile}$$

$$a_1 + ja_2 = 0.005{,}914 + j\ 0.009{,}028.$$

The real attenuation constant a_1 is thus 0.005,914 per mile. The wave-length constant a_2 is 0.009,028 radians per mile.

The wave-length λ by (4) is $\dfrac{6.283}{0.009{,}028} = 695.6$ miles.

The wave-velocity v by (9) is $\dfrac{1256.6}{0.009{,}028} = 139{,}200$ miles per second.

Since $\epsilon^{-La_1} = 0.5$ when $La_1 = 0.693{,}15$ . . (11) the waves will have shrunk to half amplitude after running a distance of $\dfrac{0.69315}{a_1}$ miles (or kilometers). This distance which waves can cover before shrinking to half size may be called the *semi-amplitude range* and be denoted by $L_{\frac{1}{2}}$. In the case here considered $L_{\frac{1}{2}} = \dfrac{0.693{,}15}{0.005{,}914} = 117.2$ miles.

If we insert the kilometre values of r, l, g and c in the formula, we obtain $a = 0.006{,}706 \,\underline{|\ 56°.47'} = 0.003{,}673 + j0.005{,}61$ per kilometre; from which the real attenuation constant is 0.003,673 per kilometre; the wave-length constant 0.005,61

radians per kilometre; the wave length λ, by (4) is $\dfrac{6.2832}{0.005{,}61} =$ 1,119.5 kilometers; the wave-velocity v by (9) is $\dfrac{1{,}256.6}{0.005{,}61} =$ 224,000 kilometres per second; the semi-amplitude range $L_{\frac{1}{2}}$ by (11) is $\dfrac{0.693{,}15}{0.003{,}673} = 188.7$ kilometres. The velocity v is in this instance only about 75 per cent of that in free air, mainly owing to the ohmic resistance in the wire. If the wire be assumed resistanceless, or of infinite conductivity, $r = 0$ in (10) and the velocity v would become 296,400 kilometres per second; or 98.8 per cent. of that of free waves in air.

Formula (10) shows that as the impressed frequency increases, the vector attenuation-constant also increases. Thus, in kilometre units, the line above considered has the following values of vector attenuation-constant, real attenuation-constant, wave-length-constant, wave-length, wave-velocity, and semi-amplitude range.

Table I.

For single-line copper wires #10 A. W. G. 0.2589 cm. diam. at interaxial distance of 30.48 cms. $r = 3.293$, $l = 0.00142$, $g = 0$, $c = 0.996{,}4 \times 10^{-8}$ kilometre units.

n	ω	α		α_1	α_2	λ	v	%	$L_{\frac{1}{2}}$
cycles per second	radians per second	vector attenuation constant per kilometre		real attenuation constant per kilometre	radians per kilometre	kilometres	kilometres per second	free air velocity	kilometres
7.96	50	0.001,281	45°.30′	0.000,898	0.000,913,4	6,880.	54,750	18.25	772.2
15.92	100	0.001,812	46°	0.001,259	0.001,303	4,822.	76,750	25.6	550.5
39.80	250	0.002,869	47°.29′	0.001,939	0.002,114	2,972.	118,300	39.4	357.4
79.60	500	0.004,080	49°.55′	0.002,627	0.003,122	2,012.	169,154	53.4	263.8
159.2	1,000	0.005,892	54°.34′	0.003,417	0.004,80	1,309.	208,330	69.4	202.8
200.	1,257	0.006,706	56°.47′	0.003,673	0.005,61	1,120.	224,000	74.7	188.7
398.	2,500	0.010,42	65°.28′	0.004,326	0.009,48	662.8	263,700	87.9	160.2
796.	5,000	0.018,12	75°.01′	0.004,684	0.017,51	358.8	285,600	95.5	148.0
1,592.	10,000	0.034,42	81°.57′	0.004,819	0.034,08	184.3	293,430	97.8	143.8
15,920.	100,000	0.337,4	89°.11′	0.004,859	0.337,3	18.62	296,470	98.8	142.6

Fig. 5 indicates by the curved line OAA, the locus of the vector attenuation-constant for different frequencies, according to the entries of Table I. It is evident that for frequencies

above 400 cycles per second the real attenuation-constant increases slowly and always lies theoretically below 0.005; while the wave-length-constant goes on increasing almost in direct proportion to the frequency.

In cable circuits, when the capacity is relatively large and the inductance very small, the attenuation-constant vector follows a different course. Thus, taking telephone cable consist-

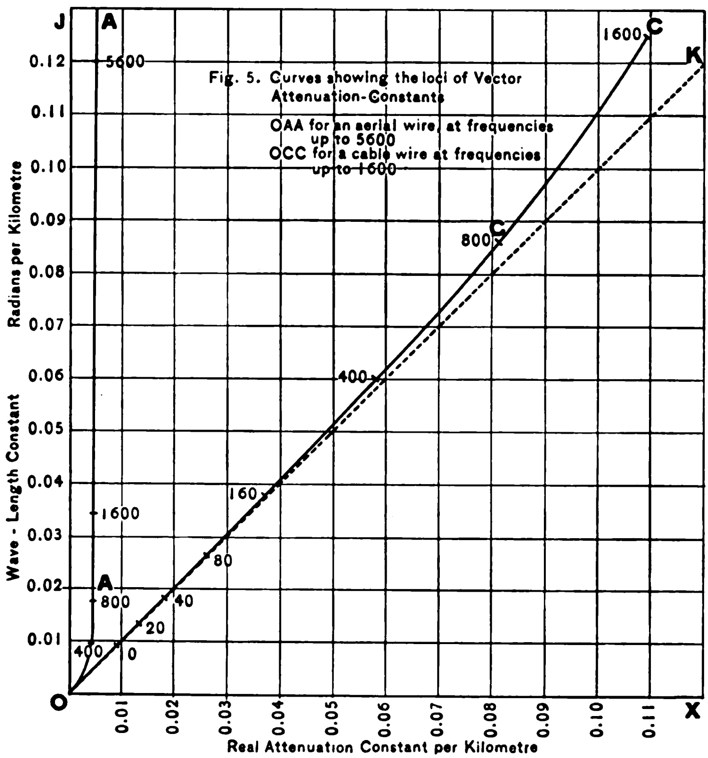

Fig. 5. Curves showing the loci of Vector Attenuation-Constants
OAA for an aerial wire, at frequencies up to 5600
OCC for a cable wire at frequencies up to 1600

ing of twisted pairs of #19 A. W. G. paper-covered copper wire (diameter 0.035,89″ or 0.091,2 cm.) with a resistance per loop-mile of 90 ohms, a capacity per loop-mile of 0.08 microfarad and an inductance per loop-mile of 0.563 millihenry, the corresponding single-wire values per kilometre are: —

$r = 27.96$ ohms; $l = 0.000,35$ henry; $g = 0$.

$c = 0.994 \times 10^{-}$ farad.

With these values we obtain by formulae (4), (9), (10) and (11) Table II.

Table II.

For single-line copper wires in twisted pair cables #19 A. W. G. 0.0912 cm. diam.

n cycles per second	ω radians per second	a attenuation constant per kilometre		a_1 real attenuation constant per kilometre	a_2 radians per kilometre	λ kilometres	v kilometres per second	% free air velocity	$L_{\frac{1}{2}}$ kilometres
9.95	62.5	0.013,18	45°.0′	0.009,32	0.009,32	674.1	6,706	2.2	74.38
19.9	125	0.018,62	45°.0′	0.013,17	0.013,17	477.1	9,492	3.2	52.63
39.8	250	0.026,36	45°.06′	0.017,90	0.017,96	349.8	13,920	4.6	38.72
79.6	500	0.037,24	45°.10′	0.026,26	0.026,41	237.9	18,930	6.3	26.39
159.2	1,000	0.052,72	45°.22′	0.037,04	0,037,52	167.5	26,650	8.9	18.72
397.9	2,500	0.083,35	45°.54′	0.058,0	0.059,86	105.0	41,76[illegible]	13.9	11.95
796.	5,000	0.118,0	46°.48′	0.080,79	0.086,02	73.04	58,130	19.4	8.58
1592.	10,000	0.167,4	48°.34′	0,108,8	0.125,5	50.06	79,670	26.6	6.37

The locus of these vector attenuation-constants is shown in Fig. 5 by the curve OCC. It is clear from the Figure that when a line has relatively large inductance with relatively low capacity and resistance, the vector attenuation-constant approximates to the straight line OJ, with a correspondingly small real attenuation constant. When, however, the capacity and resistance are large and the inductance small, the vector attenuation constant approximates to the straight line OK inclined 45° to OJ and OX. The real attenuation-constant, as found by the projection of the vector upon OX, will then be relatively large and will approximate in magnitude to the value

$$a_1 = \sqrt{\frac{cr\omega}{2}} \quad \text{per mile (or kilometre)} \qquad (12)$$

For the telephone cable above considered, this becomes

$$a_1 = 0.001{,}179\sqrt{\omega} \quad \text{per kilometre} \qquad (13)$$

For a submarine telegraph cable with 3.041 ohms per naut, 0.3728 microfarad per naut and negligible inductance

$$a_1 = 0.000{,}574{,}5\sqrt{\omega} \quad \text{per kilometre} \qquad (14)$$

In any line the real attenuation constant tends to a limiting value as the frequency increases. This limit is

$$a_1 = \frac{\frac{r}{2}}{\sqrt{\frac{l}{c}}} \quad \text{per mile or kilometre.} \qquad (15)$$

Thus for the aerial wires above considered, $\sqrt{\frac{l}{c}} = 338.6$ ohms and $\frac{r}{2} = 1.647$ ohms per kilometre. Consequently the limiting value of the real attenuation constant is $\frac{1.647}{338.6} = 0.004,864$ per kilometre. For the cable wires above considered, $\sqrt{\frac{l}{c}} = 59.34$ ohms, and $\frac{r}{2} = 13.98$ ohms per kilometre. Consequently the limiting value is $\frac{13.98}{59.34} = 0.235,6$ per kilometre. These results, taken in connection with Tables I and II and the curves of Fig. 5, demonstrate clearly the advantages possessed by aerial wires over cabled wires in the transmission of high-frequency alternating-current waves, as in telephony.

Initial Sending-End Impedance. Every line or circuit possesses a particular impedance which it offers to impressed alternating-current waves of a given frequency at the outset of their career. The impedance is offered at the sending end of the line and is, therefore, a sending-end impedance, as distinguished from the impedance offered at the receiving end. Moreover, it is an *initial* sending-end impedance, or an impedance to the freshly outgoing waves, as distinguished from the impedance presented at the sending end to the entire assemblage of waves finally flowing into the circuit after a steady state has been attained, and when many attenuated reflections of waves, that have run to and fro over the circuit, may be included along with freshly outgoing waves from the alternating source. The initial sending-end impedance may be denoted by the symbol z_0. The formula is

$$z_0 = \sqrt{\frac{r + jl\omega}{g + jc\omega}} \quad \text{ohms} \quad . \quad . \quad . \qquad (16)$$

For very high frequencies, and also for moderate frequencies in

cases where r and g are small with respect to $l\omega$ and $c\omega$ respectively, the value of z_0 tends to the limit

$$z_0 = \sqrt{\frac{l}{c}} \quad \text{ohms} \quad . \quad . \quad . \quad . \quad (17)$$

which value is sometimes called the surge-impedance of a line; or the impedance that the line tends to offer to its own free oscillations or surges.

The sending-end impedance of a metallic-circuit or looped conductor as in Fig. 1 is double that of a single-wire conductor as in Fig. 3. Whereas, therefore, the attenuation constant of a circuit is numerically the same, whether we consider the loop-mile or the wire-mile, the sending-end impedance of the loop-mile is double that of the wire-mile. As, however, the impressed e. m. f. on the loop circuit of Fig. 1 is double that impressed on each line in Fig. 3, the current flowing will be the same in either case. Table III sets forth the initial sending-end impedance of the aerial line already considered.

Table III.

Initial Sending-End Impedance per Single Wire for a pair of #10 A. W. G. Copper wires (0.1019″ or 0.2589 cm.) interaxially separated 1 foot (30.48 cms.) at different impressed frequencies.

n cycles per second	ω radians per second	z_0 vector ohms		z_0 complex quantity ohms	
7.95	50	2,570.	$-44°.30'$	1,833.	$-j\,1,801$
15.9	100	1,818.	$-44°.00'$	1,308.	$-j\,1,216.$
39.8	250	1,152.	$-42°.32'$	849.	$-j\,778.8$
79.6	500	819.0	$-40°.05'$	626.7	$-j\,527.4$
159.2	1,000	591.4	$-35°.26'$	481.9	$-j\,342.9$
397.9	2,500	418.4	$-24°.32'$	380.6	$-j\,173.7$
795.8	5,000	363.7	$-14°.59'$	351.3	$-j\,94.02$
1,592.	10,000	345.4	$-8°.03'$	342.0	$-j\,48.36$
7,958.	50,000	338.8	$-1°.39'$	337.4	$-j\,9.76$
15,920.	100,000	338.7	$-0°.50'$	338.5	$-j\,4.93$

The preceding table expresses the impedance z_0 both as a vector and as a complex quantity. Thus at the frequency of 795.8 cycles per second (5,000 radians per second) the impedance z_0 is $363.7 \,\overline{|\,14°.59'} = 351.3 - j94.02$ ohms for each wire; so that the circuit would offer $727.4 \,\overline{|\,14°.59} = 702.6 - j188.0$ ohms.

The curve AA in Fig. 6 gives the locus of z_0 in accordance with the entries of the preceding table. The impedance diminishes both in magnitude and in phase-angle as the frequency is increased. Above 800 cycles per second, however, the diminution is very small.

The broken curve CC in Fig. 6 gives the locus of z_0 for each wire of the twisted cable pairs above considered, in accordance with the entries of Table IV.

Table IV.

Initial Sending-End Impedance per Single Wire for a twisted pair of #19 A. W. G. copper wires paper covered in cable.

n cycles per second	ω radians per second	z_0 vector ohms		z_0 complex quantity ohms	
9.95	62.5	2,122.	$-45°$.	1,500.	$-j\,1{,}500.$
19.9	125.	1,500.	$-44°.58'$	1,061.	$-j\,1{,}060.$
39.8	250.	1,061.	$-44°.55'$	751.2	$-j\,749.1$
79.6	500.	750.1	$-44°.50'$	531.9	$-j\,528.9$
159.2	1,000.	530.4	$-44°.39'$	377.5	$-j\,372.8$
397.9	2,500.	335.4	$-44°.07'$	240.8	$-j\,233.5$
795.8	5,000.	237.4	$-43°.13'$	173.	$-j\,162.6$
1,591.6	10,000.	168.4	$-41°.26'$	126.3	$-j\,111.4$
15,916.	100,000.	67.12	$-19°.19'$	63.35	$-j\,22.2$

It will be seen in Fig. 6 that for low frequencies the initial sending-end impedance of an aerial line is only slightly greater than that of the particular cable-wire selected. At a frequency of 1,600 cycles per second, however, the impedance z_0 is much greater on the aerial wire than on the cable wire. This proposition has very general application. Again, wires of low resistance and leakance with respect to reactance tend to have a relatively small angle of impedance; while, on the contrary, wires of large resistance and small reactance tend to develop an angle of $-45°$ in their impedance z_0, especially at low frequencies.

The vector attenuation-constant a and the vector impedance z_0 completely define a line or conductor. If these two vectors are known for any given frequency, the constants of the line r, l, g and c are determinable. For by (10) and (16)

$$a\,z_0 = r + jl\omega \qquad \text{ohms per mile or kilometre} \qquad (18)$$

or the product of these two vectors is the conductor impedance of the line per unit of length, from which r and l may be evaluated. Again

$$\frac{a}{z_0} = g + jc\omega \qquad \text{mhos per mile or kilometre} \qquad (19)$$

or the ratio of the two vectors is the dielectric admittance of

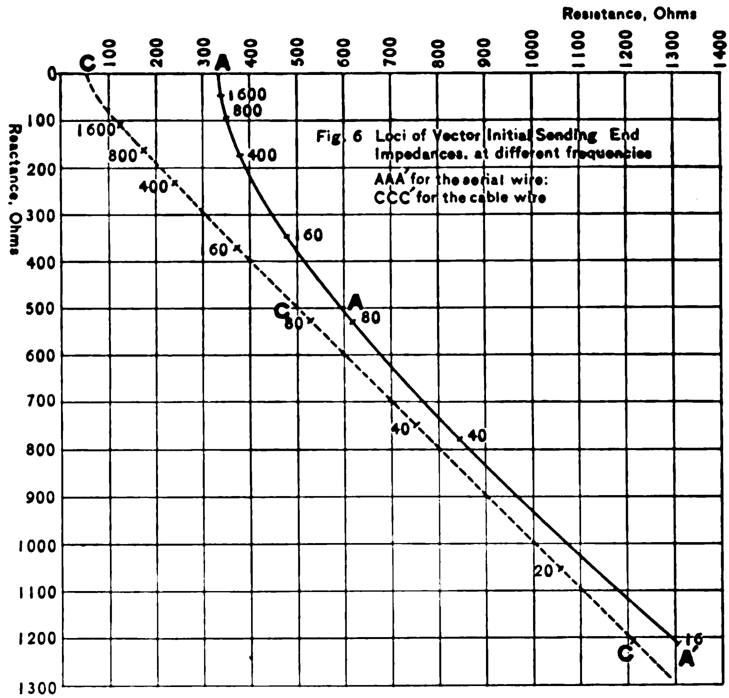

Fig. 6 Loci of Vector Initial Sending End Impedances. at different frequencies
AAA′ for the aerial wire:
CCC′ for the cable wire

the line per unit of length, from which the leakance g and capacity c may be found. Thus, Tables II and IV show that at the frequency of 796 cycles per second, ($\omega = 5000$) the attenuation constant of the cable wire is $0.118{,}0\ \underline{\vert\, 46^\circ.48'}$, per kilometre and the initial sending-end impedance is $237.4\ \overline{\vert\, 43^\circ.13'}$ ohms. The product of these is $28.0\ \underline{\vert\, 3^\circ.35'}$ ohms per kilometre $= 27.96 + j1.75$ ohms per kilometre, the linear impedance of the wire for this frequency; while the ratio of the vectors is

0.000,497 $\underline{|90^\circ}$ mho per kilometre, from which the capacity per wire mile is 0.099,4 microfarad per kilometre.

In a certain sense the characteristic vectors a and z_0 are more fundamental than the constants r, l, g and c as theoretically defining the electrical properties of a line, notwithstanding the fact that they vary with the frequency. For they are primordial in their control of those experimental phenomena from which the constants r, l, g and c are deduced.

Transmission Over an Indefinitely Long Line.

The alternating pressure and current along a line of uniform electric constants are subject to the following conditions:

$$e = \mathrm{E} \cosh \mathrm{L}_1 a - \mathrm{I} z_0 \sinh \mathrm{L}_1 a \qquad \text{volts} \qquad (20)$$

$$i = \mathrm{I} \cosh \mathrm{L}_1 a - \frac{\mathrm{E}}{z_0} \sinh \mathrm{L}_1 a \qquad \text{amperes} \qquad (21)$$

where e and i are respectively the voltage and current at the point considered distant L_1 miles (or kilometres) from the sending end; while E and I are the impressed voltage and the entering current at the sending end of the line. When the line is of such electrical length that the returning waves reflected from the distant end may be ignored, the steadily entering current I will be the same as the initial current $\frac{\mathrm{E}}{z_0}$. Consequently, for such long lines, we have

$$e = \mathrm{E} (\cosh \mathrm{L}_1 a - \sinh \mathrm{L}_1 a) = \mathrm{E}\, \epsilon^{-\mathrm{L}_1 a} \text{ volts} \qquad (22)$$

and $$i = \frac{\mathrm{E}}{z_0} (\cosh \mathrm{L}_1 a - \sinh \mathrm{L}_1 a) = \frac{\mathrm{E}}{z_0}\, \epsilon^{-\mathrm{L}_1 a} \text{ amperes} \qquad (23)$$

Thus, the voltage and current along the line are simply the normally attenuating waves emitted from the sending end, the initial impressed voltage being E virtual, or r. m. s. volts, and this attenuates after running a distance L_1 miles (or kilometres) to E $\epsilon^{-\mathrm{L}_1 a}$ volts. Similarly, the initially outgoing current $\mathrm{I}_0 = \frac{\mathrm{E}}{z_0}$ virtual or r. m. s. amperes, attenuates to $\mathrm{I}_0\, \epsilon^{-\mathrm{L}_1 a}$ after running L_1 miles, that is it attenuates $\epsilon^{-\mathrm{L}a}$ in magnitude and is retarded $\epsilon^{-\mathrm{L}_1 a_2}$ radians in phase by (2). The product $\mathrm{L}_1 a$ may

be called the *attenuation-length*. The coefficient ϵ^{-La_1} may be termed the *attenuation coefficient*.

As an example, we may consider a circuit length of 100 miles (160.9 kilometres) of the twisted pair cable of #19 A. W. G. copper wires already referred to, subjected to an impressed e. m. f. of 4 volts at a frequency of 796 cycles per second. This will correspond to 2 volts on each wire in the arrangement of Fig. 3. Table II gives the attenuation constant at $0.118 \underline{|46^\circ.48'} = 0.080{,}79 + j0.086{,}02$ per kilometre; while Table IV gives the initial sending-end impedance as $237.4 \overline{|43^\circ.13'}$ ohms. The initially outgoing current on each wire will therefore be $\frac{2}{237.4 \overline{|43^\circ.13'}} = 0.008{,}425 \underline{|43^\circ.13'}$ amperes; or 8.425 milliamperes leading the impressed e. m. f. by 43°.13′, or nearly $\frac{1}{8}$th of a cycle. Because the cable is chosen so long, and the waves that return reflected from the distant end are so very minute, the outgoing current in the steady state has the same strength as the initially outgoing current. At a distance of $L_1 = 30$ miles say, (48.28 kilometres) the attenuation-length La_1 will be $48.28 \times 0.080{,}79 = 3.901$. The attenuation-coefficient will be $\epsilon^{-3.901} = \frac{1}{49.43} = 0.020{,}23$. The voltage will have fallen to $2 \times 0.020{,}23 = 0.040{,}46$ volt. The current strength will have fallen to $8.425 \underline{|43^\circ.13'} \times 0.020{,}23 = 0.170{,}4 \underline{|43^\circ.13'}$ milliamperes, the current still leading the local voltage by this phase. Both the current and pressure will, however, have been retarded in the transmission by $48.28 \times 0.086{,}02 = 4.153$ radians or 238°; so that the full expression of voltage and current for the point considered, with reference to the phase of the e. m. f. impressed at the sending end is

$$e = 0.040{,}46 \overline{|238^\circ} \quad \text{volt}$$

$$i = 0.170{,}4 \overline{|194^\circ.47'} \quad \text{milliampere}$$

The ratio of which is $237.4 \underline{|43^\circ.13'}$ ohms, or z_0.

Table V gives the voltage and current in each wire of the circuit* for varying distances L_1 miles from the sending end.

Table V.

Attenuation-lengths and Attenuation-Coefficients for Cable Circuit at the frequency of 796 v or $\omega = 5{,}000$.

L_1		$L_1 a$ kilometric units		$\epsilon^{-L_1 a}$		e	i
miles	kilometres	$L_1 a_1$	$L_1 a_2$	attenuation coefficient	lag	volts	milliamperes
0	0.	0.	0.	1.0	0°.	2.0	8.425 | 43°.13′
1	1.609	0.13	0.138,4	0.878,1	7°.55′	1.756,2 | 7°.55′	7.398 | 35°.18′
2	3.219	0.26	0.276,9	0 771,1	15°.50′	1.542 | 15° 50′	6.498 | 27.°23′
5	8.046	0.65	0.692,2	0.522,1	39°.40′	1.044 | 39°.40′	4.399 | 3°.33′
10	16.09	1.30	1.384	0.272,5	79°.20′	0.545 | 79°.20′	2.296 | 36° 7′
20	32.19	2.60	2.769	0.074,31	158°.40′	0.149 | 158°.40′	0 626 | 115°.27′
30	48.28	3.90	4.153	0.020,23	238°.0′	0.040,5 | 238°	0.170 | 194°.47′
50	80.46	6.50	6 922	0.001,503	396°.36′	0.003 | 396°.36′	0.013 | 353°.23′

* Compare Curve 1, Fig. 1, Dr. H. V. Hayes "Loaded Telephone Lines in Practice" Trans. International Electrical Congress, St. Louis, 1904. Vol. III, p. 643.

(*To be continued.*)

HARVARD ENGINEERING JOURNAL.

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Editorial.

IT gives us great pleasure to announce that Prof. L. S. Marks has been elected auditor of the JOURNAL and that Mr. G. A. McKay, '08, of Danbury, Conn., has been elected a member of the Board of Editors.

Below we present the names of the officers of the various Scientific Societies and Clubs associated with the Division of Engineering.

These Clubs are in general open to all students who may be interested. They all have the common purpose of promoting the discussion of Engineering subjects together with a pleasant social intercourse of members.

Men wishing to join these organizations should communicate with the officers below.

Harvard Engineering Society.

Annual dues, $1.50.

Subscription to the Harvard Engineering Journal together with membership in the Society, $2.00 yearly.

Meetings monthly. Refreshments.

President, W. C. Durfee 2d '04, Jamaica Plain.
Secretary, H. P. Forté '08, 13 Stoughton Hall.
Treasurer, Wm. A. Spencer '06, 39 Thayer Hall.
Adviser, Prof. I. N. Hollis,
Graduate Secretary, Mr. S. E. Whiting, 11 Ware Street.

Harvard Electrical Club.

Annual dues, $1.00.
Initiation fee, $0.50.

Lectures by practising engineers.

President, J. H. Bucke '06, 10 Andrew St.
Secretary, W. K. Cabot '07, 3 Ellsworth Park.
Treasurer, W. F. Barklage '06, 12 Holworthy Hall.

Harvard Mechanical Club.

Annual dues, $1.00.
Initiation fee, $0.50.

Monthly Meetings.

President, H. E. Ditmars '08, 16 Hampden Hall.
Secretary, W. C. Brinton '07, 59 Thayer Hall.
Treasurer, H. P. Forté '08, 13 Stoughton Hall.

HARVARD MINING CLUB.

Annual dues, $1.00.
Initiation fee, $1.00.

Meetings held fortnightly.
Open to men interested in Mining, Metallurgy, or Economic Geology.

President, R. E. Clapp '06, Dedham.
Secretary, G. D. Scholl '06, 39 Perkins Hall.
Treasurer, J. B. Lewis, Jr. '06, 20 Stoughton Hall.

The seventh annual dinner of the Harvard Engineering Society was held on May 19, 1905, at the Hotel Westminster, Boston. Prof. Kennelly was chairman. The speakers were Prof. Wyman, Mr. Stickney of Cornell, Mr. Moyer, Mr. Ross, Mr. Newell, Mr. Durfee, Mr. Furness, Prof. Hollis.

The first regular meeting of the Engineering Society this year was held on Monday evening, Oct. 30, in Pierce Hall. Mr. C. J. H. Woodbury of the American Bell Telephone Co. delivered a lecture on "Telephone Line Engineering" illustrated by lantern slides.

The first meeting of the Harvard Electrical Club this year, was held on Thursday evening, October 19, in Pierce Hall. Many old and new members of the Club were present. There were informal talks by Prof. Kennelly and Prof. Adams.

The Harvard Mining Club held its first meeting in the Harvard Union on Friday, Oct. 20. The meeting was addressed by Prof. H. L. Smyth.

The Harvard Mechanical Club met on November 15. Mr. H. E. Duncan of the American Waltham Watch Co., gave a description of the "Mechanism of the Pocket Watch." On the next two days, November 16 and 17, the members of the Mechanical Club visited the works of the Watch Company in Waltham.

Notes.

Prof. I. N. Hollis is now in Geneva, Switzerland, with his family. He is expected to return for the second half year.

Prof. F. L. Kennedy is on leave of absence for a year. He will spend his time in studying the draughting-room methods of various manufacturing establishments. He is now with the General Electric Co. in Lynn, Mass. His address is 202 Ocean St., Lynn.

E. B. Whitney and W. V. Moses are also working in the draughting room of the General Electric Co.

After a year of absence Prof. C. A. Adams has returned to Harvard, to resume his work in the Electrical Department.

Mr. C. O. Mailloux who has recently written for the JOURNAL on "Train Resistance," is giving a course of lectures in the Brooklyn Polytechnic Institute. His lectures will cover the subject of "Electric Train Movement."

J. J. Eaton, '96, is Superintendent of the Philippine School of Arts and Trades at Manilla, P. I.

H. W. Howe, '97, and F. H. Eichorn, '01, are working in Boston in connection with the Charles River Dam.

E. W. Stevens, '99, is in Boston with a firm of bankers and brokers.

Granville Johnson, '03, of the 1902 JOURNAL Board is Assistant Chief Engineer of the Union Electric Light and Power Co., St. Louis, Mo.

Kenneth Sherburne, '03, is in the draughting room of the Sturtevant Blower Co.

E. J. Whittier, '01, is in the purchasing agent's department of the Agricultural Chemical Co. He is stationed in New York.

H. M. Hale, '04, is Assistant Engineer of the Board of Rapid Transit, R. R. Commrs. His address is 231 W. 125th St., New York, N. Y.

Louis Ross, '04, is on the U. S. Geological Survey (Hydrographic Branch) Washington, D. C. During the summer he was in charge of a party which surveyed some hundred miles of the Roanoke River in Virginia. At present, he is in Washington working up results for publication. Address,— Care U. S. Geological Survey, Washington, D. C.

A. Locke, '04, and Guy Stoltz, '05, have gone into partnership as mining Engineers in Salt Lake City, Utah.

P. A. Marean, '05, is at Purdue University acting as research assistant to Prof. Goss in locomotive testing.

Aldrich Durant, '03, is in Cambridge assisting Prof. Marks in the Mechanical Engineering Courses of the Senior year.

H. W. Sturgis, '05, is working under Prof. Adams on motor driven sugar drying machinery at the works of the American Tool & Machine Co., Brooklyn.

W. M. Gould, '05, is engaged in telephone work for the American Telephone and Telegraph Co.

W. Lewis, '05, is learning Cotton Machinery with the Draper Co., Hopedale, Mass.

The following men are reported from Schenectady working for the General Electric Company. C. J. Cutting '05, F. P. Coffin '04, D. Dubois '03, F. H. Poor '04, H. D. Kernan '05, H. Morgan '06, E. N. Willis '03, A. H. Train '05, D. L. Furness '05, W. O. Batchelder '05.

J. R. Lewis, '05, and Bryant White, '05, are working for the Bullock Electric Manufacturing Co., in Cincinnati.

E. C. Stone, '04, F. W. Cloud, '05, P. M. Patterson, '05, are in Pittsburg with the Westinghouse Electric and Mfg. Co.

S. F. Rockwell, '00, is with Davis & Furber Machine Co., Andover, Mass.

A. L. Haskell, '03, is superintendent of construction work for the National Underground Cable Co., Pittsburgh.

Architectural Notes.

L. P. Burnham, '02A, holder of the Nelson Robinson Jr. Travelling Fellowship in Architecture for 1903–04, and of the Julia Amory Appleton Fellowship for 1904–05, has settled down in Paris to work for another winter.

A. H. Blevins, '98A, of the firm of Newhall and Blevins is one of the architects of a large new apartment house erected during the past summer on Brattle Street, Cambridge.

C. H. Ely, Sp. '98, who is in independent practise in Beverly, Mass., was the architect for a new building recently erected for Dummer Academy near Newburyport, Mass.

C. F. Gould, '98, spent the summer in San Francisco, working under the direction of D. H. Burnham *h*'93, of Chicago, the architect who has been so largely concerned in the recent work of the architectural development of Washington and Cleveland. Mr. Burnham has now prepared plans for future development of San Francisco, which on account of its exceptional situation bids fair to be one of the most beautiful cities in the country, if not in the world.

T. M. Hastings, '98A, until recently in independent practise in Philadelphia is at present the junior partner in the firm of Brockie and Hastings in that city.

A. E. Hoyle, '04A, has been appointed Assistant in Architecture in Harvard University.

J. L. Peabody, '03, and H. S. Cobb, Jr., '04, are working at the Ecole des Beaux Arts in Paris.

C. R. Wait, '03A, holder of the Nelson Robinson Travelling Fellowship in Architecture for 1904–05 has recently returned to this country.

W. L. Mowll, '99A, has been appointed Assistant Professor in Architecture at Harvard University.

W. E. C. Nazro, '98A, is welfare agent for the Plymouth Cordage Company at Plymouth, Mass. In that capacity and as the Company's architect he is concerned with the housing, general comfort and recreation of its employés. He has recently been employed by the United States Government to study the welfare of the workmen employed upon the Panama Canal.

Exchanges.

The Journal wishes to acknowledge the following Exchanges: The Iowa Engineer, Journal of the Association of Engineering Societies, Stevens Institute Indicator, Journal of the Franklin Institute, Engineering Press Index, Engineering Index, Harvard Graduates' Magazine, The Wisconsin Engineer, Journal of the Western Society of Engineers, The Technical World, Technology Review, The Technograph, The Sibley Journal of Engineering, The Polytechnic, The Michigan Technique, Electrical Club Journal, Proceedings of the American Society of Mechanical Engineers, Proceedings of the American Institute of Electrical Engineers, Proceedings of the American Society of Civil Engineers, Journal of Worcester Polytechnic Institute.

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